Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-CISD–2007/003 August 2007

Ship Systems Integration & Design Department

Technical Report

DUKW 21 – Amphibious Cargo Transfer from Ship to Shore

By

Franklin Gonzales

Rebecca Orme

Austin Ruppert

Joseph Schaffer

Unrestricted Distribution

NSWCCD-CISD–2007/003

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
10-August-2007

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
21-May-2007 – 10-Aug-2007

4. TITLE AND SUBTITLE
DUKW 21 – Amphibious Cargo Transfer from Ship to Shore

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Franklin Gonzales, Rebecca Orme Austin Ruppert, Joseph Schaffer

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)
Naval Surface Warfare Center
Carderock Division
9500 Macarthur Boulevard
West Bethesda, MD 20817-5700

8. PERFORMING ORGANIZATION REPORT NUMBER
NSWCCD-CISD-2007/003

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Unrestricted Distribution

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Amphibious vehicles have long been recognized as important logistic tools for the armed forces. The ability to provide a single vehicle supply line over land and water make them the most direct, adaptable, and cost effective method for re-supply operations.
Historically, amphibious vehicles were optimized for either traversing aquatic or terrestrial environments leading to vehicles that lacked all-round performance and were often unreliable and thus less effective tools for the military. Using modern technology, the DUKW 21 design team's object was to develop a viable amphibious transport vehicle that was as much at home in the water as on land. The DUKW 21 project design delivers a new amphibious transport vehicle concept capable of delivering a 20-foot fully loaded ISO container from a position 5 nm at sea to a point 5 nm in land at a minimum cruising speed of 15 knots. It also has the ability to do this autonomously by incorporating an array of sensor and guidance systems leading to lower manning levels.
After initial stability, resistance, and mechanical system analysis, it was determined the DUKW 21 is a feasible design. The DUKW 21 has the ability to meet the main design requirements with currently available technology and do so with minimal subsystems and complexity.

15. SUBJECT TERMS
DUKW, amphibious transport, Sea Base, SWATH, Autonomous operation, ISO container transport

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	None	55

19a. NAME OF RESPONSIBLE PERSON
Colen Kennell

19b. TELEPHONE NUMBER *(include area code)*
301-227-5468

Abstract

Amphibious vehicles have long been recognized as important logistic tools for the armed forces. The ability to provide a single vehicle supply line over land and water make them the most direct, adaptable, and cost effective method for re-supply operations. Historically, amphibious vehicles were optimized for either traversing aquatic or terrestrial environments leading to vehicles that lacked all-round performance and were often unreliable and thus less effective tools for the military. Using modern technology, the DUKW 21 design team's object was to develop a viable amphibious transport vehicle that was as much at home in the water as on land.

The DUKW 21 project design delivers a new amphibious transport vehicle concept capable of delivering a 20-foot fully loaded ISO container from a position 5 nm at sea to a point 5 nm in land at a minimum cruising speed of 15 knots. It also has the ability to do this autonomously by incorporating an array of sensor and guidance systems leading to lower manning levels.

After initial stability, resistance, and mechanical system analysis, it was determined the DUKW 21 is a feasible design. The DUKW 21 has the ability to meet the main design requirements with currently available technology and do so with minimal subsystems and complexity.

Acknowledgments

This report is the culmination of work conducted by students hired under the National Research Enterprise Intern Program sponsored by the Office of Naval Research. This program provides an opportunity for students to participate in research at a Department of Navy laboratory for 10 weeks during the summer. The goals of the program are to encourage participating students to pursue science and engineering careers, to further education via mentoring by laboratory personnel and their participation in research, and to make them aware of Navy research and technology efforts, which can lead to future employment.

At the Naval Surface Warfare Center Carderock Division, the single largest employer of summer interns is the Center for Innovation in Ship Design (CISD), which is part of the Ship Systems Integration and Design Department. The intern program is just one way in which CISD fulfils its role of conducting student outreach and developing ship designers.

The student team consisted of:

Franklin Gonzales

Rebecca Orme

Austin Ruppert

Joseph Schaffer

The team would like to acknowledge Steve Ouimette, Dr. Chris Dicks, Dr. Colen Kennell, and LCdr Mark Read for their assistance.

Executive Summary

The USN is currently developing the Sea Base concept to allow it to operate in hostile environments where port facilities are not readily available. One challenge of this concept is the development of a supply chain to transport cargo from ships to shore. Currently, the USN relies on large transport ships, such as Large Medium-Speed Ro-Ro (LMSR) vessels and full port facilities to deliver large amounts of cargo to shore. Without a port facility, the Navy does not have an effective means to transfer large amounts of cargo to shore.

Current solutions involve either a landing craft/land vehicle combination, or helicopters making many trips transporting small pallets. These methods are intricate, expensive, and slow.

The DUKW 21 concept seeks to provide a means to transport large amounts of cargo to shore quickly and inexpensively. The DUKW 21 will perform the difficult transition mission between the Sea Base or amphibious transport vessels and inland supply. A single DUKW 21 will be able to load a 20-foot, 24 metric ton ISO container at the Sea Base, carry it inland, and unload the container, quickly and autonomously.
The following initial requirements constrained the DUKW 21 design:

- Operate in Sea State 2;
- Make deliveries from 5 nm offshore to 5 nm inland;
- Cruise at 15 knots in water and 30 kmh on land;
- Climb standard beaches (1:50 gradient);
- Load/Unload the ISO container automatically;
- Controlled by either a single crew member or by automatic, unmanned control;
- Deliver 10 ISO containers without refueling; and
- Enter the well deck of an LPD.

Several concepts were judged by their ability to meet the design goals and one was determined to be the most capable. The final design is a SWATH hulled vehicle with a track system recessed into the hulls and a cross structure consisting of two arches that also act as a crane to lift the ISO container. This combination was selected because of the inherent stability and decreased drag provided by the SWATH design.

The DUKW 21 will continuously be exposed to the harsh marine beaching environment so a simple robust design would be preferred. The simplicity and strength provided by the arch cross structure is a fine start to this, and when paired in conjunction with the modulated Swath hulls the system is nearly complete.

After initial stability, resistance, and mechanical system analysis it was determined that the DUKW 21 is able to meet the mission criteria with minimal system complexity. The unique hull configuration required the use of an integrated electric power transmission to avoid the extreme complexity of a mechanical transmission system. The integrated electrical system allows a single gas turbine generator to provide power for water propulsion, land propulsion, crane operation, auxiliary systems and electronics.

The DUKW 21 is an innovative, balanced design using the latest and most promising technologies available to minimize weight, fuel consumption, maintenance difficulties, and manning requirements resulting in a vehicle that can help the USN meet its needs for the future. With initial feasibility proven it is recommended that the DUKW 21 design be developed in more detail.

Table of Contents

List of Figures

List of Tables

Introduction

Background

The original DUKW was designed to serve as a connection between land and sea. The DUKW was built using an existing military truck, the GMC CCKW, by adding a hull, propeller, and bilge pump system.

There was extensive use of the DUKW in the Second World War, including the Marshal Islands campaign, the Rhine River Crossing, landings at Saipan, Tinian and Iwo Jima, and in Guam. "Between 9 September and 1 October 1943, 90 landing craft and 150 DUKWs moved 190,000 troops, 30,000 vehicles and 12,000 tons of supplies across the invasion beaches to Salerno." (UATM, 2007) The DUKWs allowed ships to stay offshore thereby reducing beach congestion and danger to the supply ships from enemy fire. (Wells, 2007) The DUKWs also served as rescue craft, retrieving troops from behind enemy lines, and as transport between the Pacific islands.

Later versions of the DUKW included the LARC (lighter, amphibious, re-supply, cargo) and the BARC (barge, amphibious, re-supply, cargo). The BARC was able to transport up to a 120,000-pound payload and included a crane to lift the containers off of the BARC. These vehicles were introduced in the Vietnam conflict and the last company operating these vehicles was decommissioned on 15 October 2001.

The Marine Corps has been using another type of amphibious vehicle known as the Amphibious Assault Vehicle (AAV) since 1972. This is a lighter vehicle designed for transporting 25 "combat loaded" marines. The AAV was intended to be a personnel carrier rather than a cargo transport. The Expeditionary Fighting Vehicle (EFV) will replace the AAV and has been designed to be faster and better protected than its predecessor.

Prior Solutions

Previously, the USN has relied on the use of a fleet of transport vehicles that perform specific functions in order to develop a supply line based at a secure port. With the introduction of the Sea Base, this may no longer be the case and the vehicles used to transport supplies must change to accommodate this operational capability. Logistical support in the past has involved the use of landing craft such as LCUs, LSTs, and LCACs in coordination with larger transport ships. This option is time consuming and adds more vessels and complications to the logistics mission. DUKW 21 will reduce the need for multiple vessels and focuses on one craft that will perform the cargo transfer from the Sea Base/amphibious transport vessel to inland mission.

Mission Statement

The DUKW 21 design team's mission is "to develop a conceptual amphibious vehicle capable of transferring a 20-ft ISO container from a vessel offshore to a point inland."

Indicative Mission

The DUKW 21's mission is to transit from its place of origin aboard an assault ship or from a Sea Base, and then complete ten round trips to a point onshore, delivering one 20-ft ISO cargo container per trip. Each delivery cycle consists of 6 stages: loading the container, traversing water, traversing land, unloading, returning across land, and returning in the water to its starting point. A model timeline was created for each of these stages so that the power requirements, fuel consumption, and speed could be determined for each stage. Additionally, by separating all the stages of one cycle it is easier to detect what problems could arise during each stage and what measures can be taken to prevent these problems.

The first stage of the mission cycle is loading the ISO container onto the DUKW 21. The DUKW 21 design must travel over a container it intends to load. One way a cargo ship would interface with the DUKW is through a roll-on roll-off discharge facility, such as the new Improved Navy Lighterage System (INLS). The ship would crane the container down to the INLS platform, then the DUKW 21 would roll onto the platform, position itself directly over the container, lower its spreader bar, secure the container, and then lift it into the transit position. Then the DUKW would roll back into the water and engage its water propulsors. It was estimated that this stage of the mission would take about 5 minutes at 10% power.

The second stage of the cycle is traversing five nautical miles to the shore at full speed. At a speed of 16 knots, or about 18.4 miles per hour, the vehicle will reach the beach in about 18 to 20 minutes. This estimate could vary depending on the current sea state. During this stage of the mission cycle, the DUKW 21 will be running at full power.

The third stage of the mission is transitioning through the surf zone and then traversing ashore to a point five nautical miles inland. Once the DUKW 21 hits the beach, it will engage the track motors to crawl up the beach slope. As the DUKW leaves the water, the water propulsors will be retracted upwards. DUKW 21's land cruising speed is at least 30 kmh or 18.6 mph. It will take about 18 to 20 minutes to traverse 5 nm and reach its final destination. Depending on the terrain that the vehicle will have to traverse, it will adjust its speed and vary the suspension settings for the track system. This leg of the mission presents the most challenges to the autonomous navigation and control system. The autonomous system will navigate precisely to ensure the DUKW arrives at its destination with its cargo intact.

The fourth stage of the mission is unloading the ISO container at the area designated by the forces on the ground. The DUKW 21 will arrive at the drop point and lower the ISO container straight down, releasing it on the ground. If required, the DUKW 21 will also be able to load an empty ISO container to return to the Sea Base.

The fifth and sixth stages of the trip are the return trips on land and sea. At this stage the vehicle will be lighter; however, it will also have a lower center of gravity, making it more stable.

The DUKW 21 should be able to complete 10 round trips in about 14 hours without refueling.

Mission Requirements

The following mission requirements were delivered to the design team and were meant to constrain the design so that the DUKW 21 would be able to realistically carry out its task of transferring cargo from ship to land:

- Operate in Sea State 2
- Make deliveries from 5 nm offshore to a point 5 nm inland
- Cruise at 15 knots
- Climb standard beaches (1:50 gradient)
- Load/Unload the ISO container automatically
- Controlled by either a single man crew or by automatic, unmanned control
- Deliver 10 ISO containers without refueling
- Lift a loaded 20-ft ISO container weighing 24,000kg (53,000lbs)

Assumptions

A number of requirements were assumed by the design team to facilitate the design process. The DUKW 21 was assumed to be able to:

- traverse very soft or broken ground;
- retrieve empty containers from the land drop off point; and
- use a roll-on roll-off discharge facility, such as the INLS to interface with a cargo ship.

Design Spiral Process

The design process of the DUKW 21 followed the modified ship design spiral (Figure 1.)

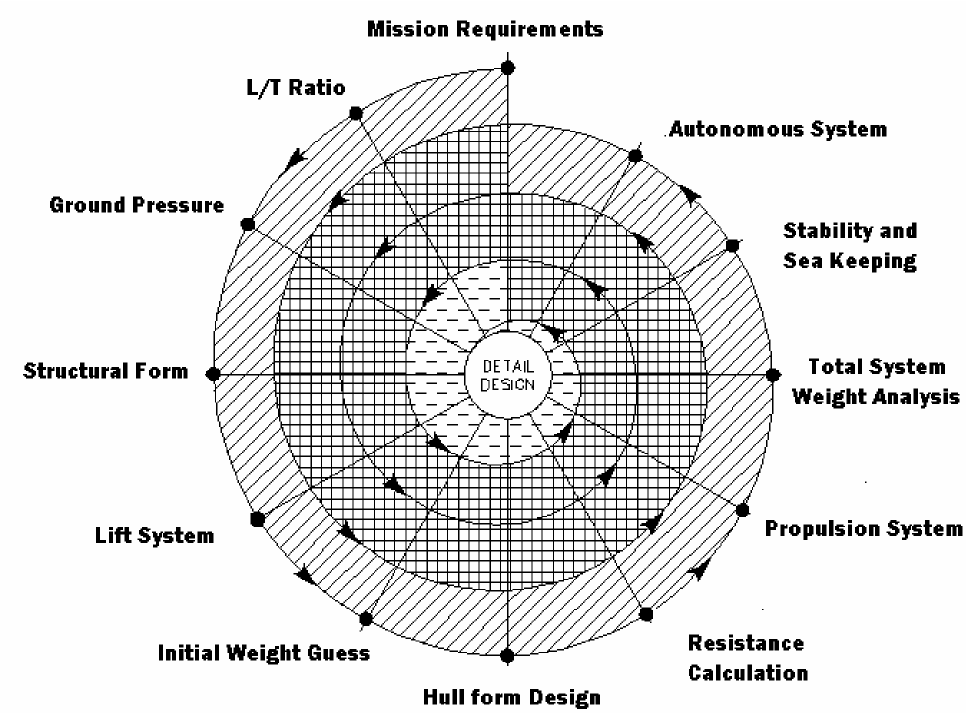


Figure 1: Design Spiral

The design priorities for the DUKW 21 were determined from its primary mission of delivering equipment to shore and being effective on both land and sea. From this, an iterative process could be derived for the mission specific needs. During this study, one revolution of the design spiral was completed. A detailed design would be needed for conformation of the team's findings.

Initial Concept

The initial concept for the DUKW 21 was inspired by revisiting existing amphibious vehicles to see if any could be modified to fit the DUKW 21 mission requirements. This led to the modified EFV shown in Figure 2.

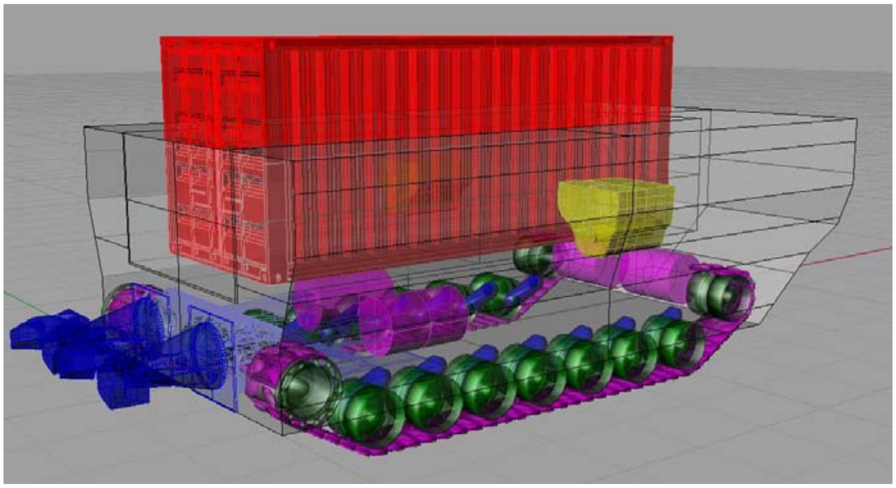


Figure 2: EFV Concept

The Modified EFV concept featured a blunt square-shaped monohull with the ISO container stowed on the top rearward platform above the propulsion subsystems. The main propulsion systems for this concept were two waterjets and a retractable track system to reduce drag.

Decision Process

The modified EFV concept presented above was likely capable of meeting the primary mission requirements but when compared against other concepts the system complexity required to overcome the high drag of the hull form was undesirable. To achieve the required cruising speeds the track system would have to be retracted into the hull in addition to some form of hull transformation capacity as seen in the EFV. The waterjets would also have to be retracted during land operations to provide ample ground clearance and so the rear ramp could be lowered for ISO dismount. Loading and unloading the ISO container would also be complicated because a large robotic arm system would be required to drag the container up and down the ramp. The difficulty of developing and implementing these complex systems decreased the overall feasibility of the design.

Several other designs were also considered. One concept was a transformable catamaran. Another used extendable outriggers on a monohull type design. Each of these designs was discarded in favor of the proposed concept.

Overview of the Final Design

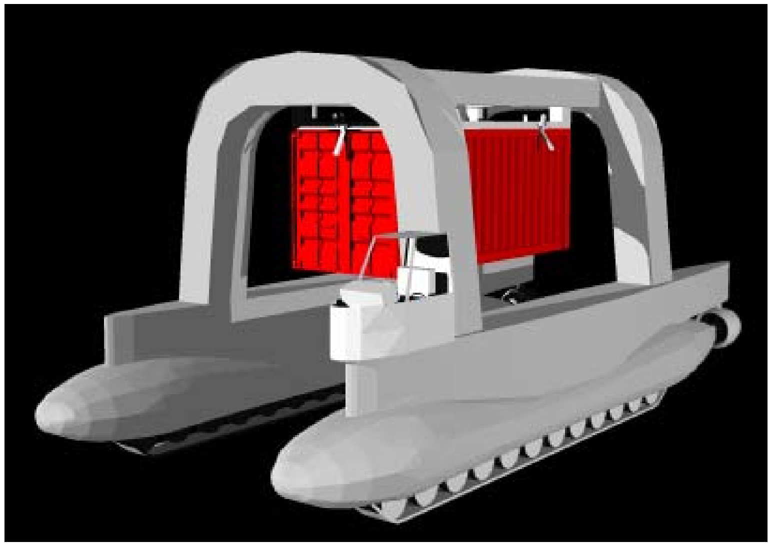


Figure 3: Final Concept

The final DUKW 21 concept is a tracked SWATH vehicle with a high arching cross structure. This design was significantly influenced by the cargo container loading and unloading requirement. A catamaran type hull form was explored for its advantages in stability, drag reduction, and opportunity for innovation. With a catamaran type hull form, it was determined that an efficient way to load and unload the container would be to lift the container straight up from the ground. The vehicle would drive directly over the container, the hulls on either side, and lift the container with a spreader bar and cables using the cross structure as a crane. This concept was deemed worthy of development.

Tracks run along the bottom of each hull for ground propulsion. An azimuthing podded propulsor is located at the aft end of each pontoon for water propulsion. The two arches that make up the cross structure are joined along the centerline of the vehicle by longitudinal beams. The container lift system is arranged along these beams. The container is lifted straight up and suspended from the arch structure during transit. A gas turbine is located on the starboard hull and a helm structure for manned control is located on the port hull.

	Metric	English
Length	16.05 m	53 ft
Width	7.62 m	25 ft
Height	7.28 m	24 ft
Weight	56,354 kg	124,239 lbs
Cruising Speed	15 knots	17.26 mi/hr
Output	1 MW	1,500 hp
Range	200 nm	230 mi
Cargo Capacity	24,000 kg	52,911 lbs
Cargo %	42.6%	

Table 1: Final Design Principal Characteristics

Structure

Hull Form

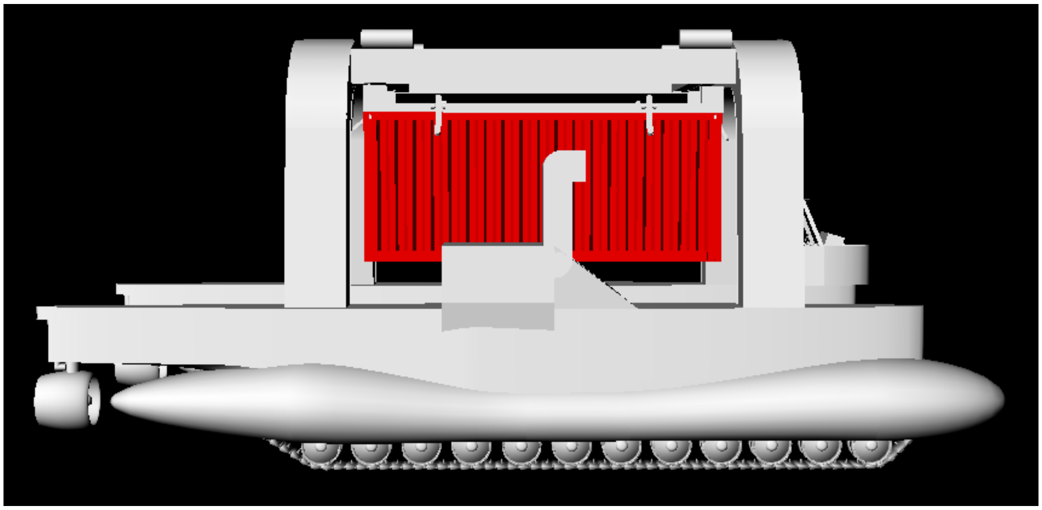


Figure 4: Hull Form

Selection of a Hull Form

The Small Waterplane Area Twin Hull (SWATH) is a ship design resembling a catamaran that minimizes the hull's waterplane area to reduce resistance and to improve seakeeping characteristics. This is achieved by locating most of the ship's displaced volume in pontoons below the waterline. SWATH hulls are inherently very stable. One reason for this is that their waterplane area is located far outboard of the vessel's centerline, which translates into a large transverse righting moment. Another reason is that the waterplane area itself is reduced. With this small waterplane area, small changes in draft equate to only small changes in buoyant force, so when waves pass over the hull form, they do not accelerate the vehicle violently.

The small waterplane area achieved in SWATH designs can also reduce overall resistance by greatly reducing wavemaking and wavebreaking resistance. The struts are long, slender foils and slip cleanly through the water compared to traditional hull types. They do not expend large amounts of energy creating large bow waves and wake, and this reduces the power needed to propel the ship. If designed properly, the twin hulls can actually create constructive interference of their bow waves, further reducing drag.

The hullform chosen for the DUKW 21, however, is not a typical SWATH hull. Its pontoons are "stubby." They are shorter and wider than most SWATH hulls. Also, the DUKW 21's hull is flat bottomed to accommodate the track system, while most SWATH hulls rise in the middle, along the "pinched" part of the hull. The extent to which these abnormalities change the behavior of the hulls is not fully understood, and needs to be examined further.

Arch

Overview of Arch Design

The twin hulls of the DUKW 21 design are connected by two arching structures rather than straight beams. Horizontal beams positioned near the upper "corners" of each arch connect the arches together. This cross structure was chosen because it allows the vehicle to drive directly over the ISO container and lift it using the arches as a crane. The container lift system is explained in detail later in the report.

Force Analysis

Force analysis of the arch structure was performed to aid in the design and weight estimate of the arches. This force analysis was undertaken using a modified transverse bending moment calculator for SWATH ships. This particular type of analysis was chosen because this bending moment should be the greatest load on the structure and therefore will be the assumed design case. The arrangement and output of the program can be found in Table 12 of Appendix B. The maximum side force was calculated to be around 13.6 MN resulting in a moment of 115,221,711 N-m. A standard marine Aluminum 5000 series was chosen for the initial weight and strength estimates. Yield strength, not ultimate tensile strength, with a factor of safety of 2 was the stress limit. After many cycles of member design and analysis, the design team chose the arch cross section shown in Figure 5. After this initial force analysis, it was determined that the arch structure alone would provide the vehicle with adequate load bearing capability and rigidity.

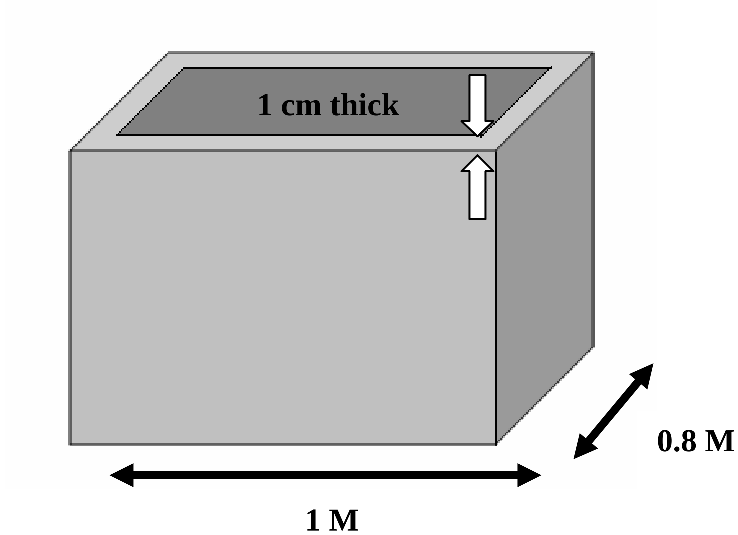


Figure 5: Structural Member

Further Structural Analysis

There are several limitations of the analysis performed that need to be taken into consideration. The design team did not have access to any analysis tools that were designed specifically for this type of structure so a "composite" program was assembled. The output of this program was checked by hand calculations. Agreement between the hand calculations and computer results suggest that they were fairly accurate but refined computer analysis should be performed. To accurately model the arch structure, sophisticated finite element analysis would be appropriate. The analysis shown here was adequate for confirming the initial feasibility of the arch design, but again, a refined analysis is recommended as the DUKW 21 is developed further.

Hydrostatic and Resistance Analysis

To perform its mission safely and reliably, the DUKW 21 needs to be stable at sea and during transition from sea to shore through the surf zone. That means it needs to be able to maintain an upright orientation when pitched and rolled by waves. The design criteria state that DUKW 21 should be able to perform its mission at a Sea State of at least 2, which means a significant wave height of at most 0.5 meters or about 2 feet. Hydrostatic analysis was conducted to determine whether the vehicle would be stable in calm seas.

Draft Heights Loaded/Unloaded

The vehicle was designed so that the loaded container would be about one meter above the calm waterline, keeping it clear of most waves at Sea State 2, and minimizing the force those waves would apply to the container and vehicle. The container weight is nearly that of the vehicle itself, and thus the draft of the vehicle in loaded condition is nearly one meter greater than the draft in the unloaded condition.

The magnitude of the changes in draft presented challenges. In the fully loaded condition, the vehicle has very little freeboard, which presents a danger that the vehicle could flood through the deck as water splashes over it. In the unloaded condition, the pontoons are not fully immersed, which significantly increases wavemaking resistance. In addition, the podded propulsors are not fully immersed, which could notably decrease propulsive efficiency. The unloaded and loaded water planes are illustrated in Figure 6.

The freeboard issue was resolved by specifying that the hull, including the turbine enclosure and helm/pilothouse structure, be watertight above the waterline as high as the turbine air intake. The issue of the pontoons and propulsors not being fully immersed is not as easily solved, but may be acceptable as is. The increased resistance of the hull form in the unloaded condition will be examined later in the “Resistance” section of the report. The efficiency of the propulsors when not fully immersed has not been examined by the DUKW 21 design team due to time constraints, but should be examined upon continuation of the design.

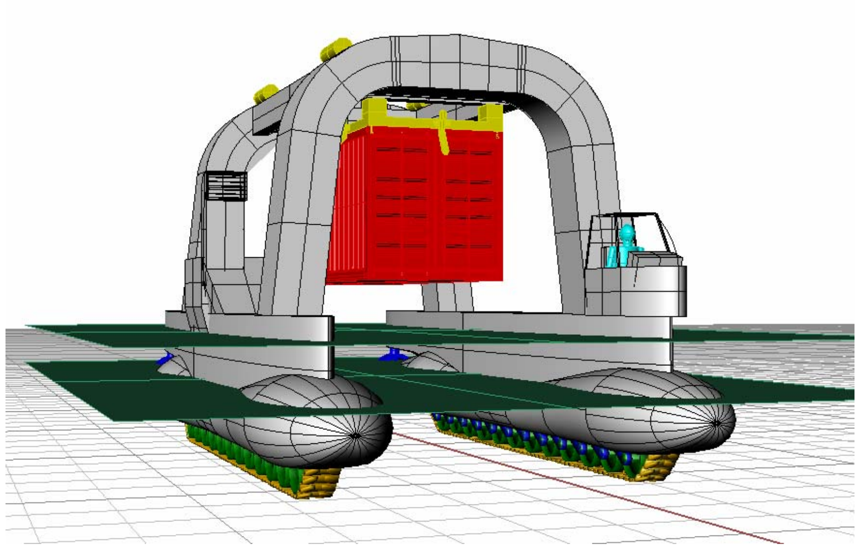


Figure 6: Draft Heights (Deep and Light)

Intact Static Stability

Intact static stability analysis was conducted for the loaded and unloaded conditions using the Rhino Marine hydrostatics analysis tool. The overall center of gravity (CG) for the vehicle was found using the Rhino 3D model of DUKW 21 and Table 15 in Appendix B. It was found that the vehicle was very stable in both the transverse and longitudinal directions. Table 2 shows the results of the stability analysis. The vehicle is watertight up to the turbine gas intake, and that intake is the limit of the downflood angle. Figures 14 and 15 in Appendix B show transverse righting arm curves for the loaded and unloaded conditions. The curves show that the righting arm (GZ) is positive up through and beyond the downflood angle. It was determined that these intact stability characteristics were more than adequate for the requirement of Sea State 2.

	loaded	unloaded
Draft	2.4 m	1.5 m
Displacement	55 mt	29 mt
GM, transverse	1.9 m	9.0 m
GM, longitudinal	4.4 m	18.8 m
Downflood Angle	34° (starboard)	43° (starboard)
GZ range	0°-34°	0°-43°

Table 2: Final Design Stability Characteristics

Resistance

Resistance calculations were conducted using a program designed to estimate resistance for SWATH hulls. The program uses potential flow and frictional resistance line analysis to accurately predict total resistance for a SWATH hull form.
Additional appendage drag caused by the tracks was estimated using the ITTC friction line and it was found that although the tracks are a major appendage, they should not

significantly increase drag at the relatively low desired cruising speed. One reason for this is that the tracks do not protrude far below the hull and thus do not present a large cross section, and so should not significantly increase form drag. The significant part of the drag caused by the tracks would be frictional, but frictional drag calculations performed for the tracks show that frictional drag on the tracks is less than two percent of the total drag for the hull at cruise speed. Figure 16 in Appendix B shows drag curves for the DUKW 21 at loaded condition.

In the unloaded condition, the pontoons of the SWATH hull are not fully submerged. This would lead to an increase in wavemaking resistance. There is also a much lower wetted surface area in unloaded condition, however, and that decreases frictional drag. The two factors tend to balance each other out so that powering requirements for the unloaded condition are similar to the fully loaded condition.

It is important to note that these calculations need to be verified with model testing. The analysis tools used were not designed specifically for a SWATH hull of the DUKW 21's shape. The hull form chosen is unique and model testing is the only way to verify this rough computer analysis with confidence.

Powering

The effective horsepower for the vehicle at cruise speeds is shown in the table below:

	loaded	unloaded
Draft	2.4 m	1.5 m
Displacement	55 mt	29 mt
EHP	515 kW @ 16 kts	511 kW @ 15kts

Table 3: Final Design Powering Characteristics

Assuming a propulsive efficiency of only 0.60, it has been determined that the DUKW 21 could easily reach cruise speeds of over 15 kts with 1 MW of power available as designed.

Components

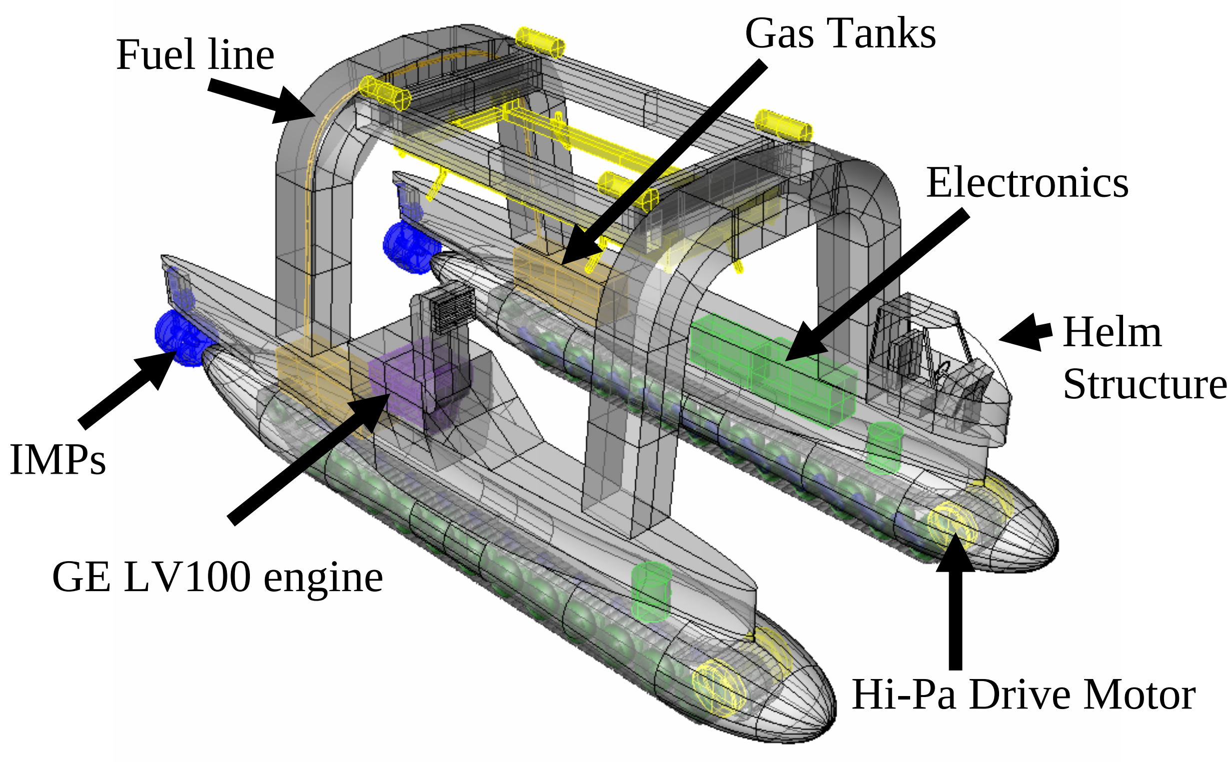


Figure 7: Component System Layout

Integrated Electric Propulsion

It was decided to employ full electric propulsion in the design of the DUKW 21. Integrated electric power (IEP) is the best choice for power transmission in the vehicle for many reasons. IEP makes the design feasible and eases arrangement difficulties. This is because the vehicle is powered by a single generator set located on the starboard side of the vehicle, but propulsion systems are located on both sides of the vehicle. Mechanical power transmission through the arch structure to the subsystems would be complicated, heavy, and inefficient, but electric power transmission through the arch is as simple as running the power cable. Fitting direct drive for both modes in each hull is also very complex and wasteful.

IEP simplifies power distribution among the land propulsion, sea propulsion, and container lift systems, all of which require significant power. Electric power transmission also allows for a smooth transition between propulsion systems, which should make beaching easier and safer.

IEP has made possible the selection of an integrated motor propulsor system for propulsion at sea. The podded propulsors are ideal for the vehicle because they are retractable, azimuthing, and self-contained. These benefits will be discussed later.

As with any IEP, the prime mover generator set can also power the vehicle's smaller systems, so a separate generator for systems such as the autonomous sensors and computers and control systems is not necessary. It has been calculated that the power requirements for the autonomous control system should be low (less than 5 kW). The propulsors should consume no more than 850kW of power, so with a single 1MW generator, it is considered that the remaining 150kW is enough to power all peripheral systems on the vehicle. Table 13 in Appendix B outlines the power requirements for DUKW 21's major systems.

Prime Mover

To propel the DUKW 21 through the water at 15 knots or higher, the vehicle needs a power generator in the one MW range. Also, a very lightweight, power dense engine is needed to minimize the weight of the vehicle. When choosing a prime mover for the DUKW, both gas turbines and diesel engines were investigated. Low and medium speed diesels were immediately eliminated due to their low power density. Some high-speed diesels were examined more closely, particularly the MTU MT883, which was chosen to power the EFV amphibious vehicle. The MT883 possesses more than enough power to propel the DUWK 21. However, while the engine is power dense for a diesel, the weight and size of the engine plus an attached electric generator was determined to be too large.

As an alternative, the new GE LV100 gas turbine engine was investigated. The LV100 gas turbine was developed in a partnership between General Electric Aviation and Honeywell International as a replacement for the proven, yet aging and breakdown prone AGP1500 M1 Abrams tank engine. The LV100 was designed to be less costly to operate than the AGP1500 through improved fuel efficiency and reduced maintenance costs. The 1,500 shaft horsepower (SHP) engine is very power dense, and, since it uses a recuperated cycle, has much better idle fuel consumption characteristics than other gas turbines.

In an article published in 2000 in the Journal of Engineering for Gas Turbines and Power, Angelo V. Koschier and Hagen R. Mauch explain how the LV100 could be coupled with a high-speed generating device to provide power for hybrid propulsion systems. The turbine generator, with the high-speed generator integrated into the turbine, would "provide in excess of 1MW of electric power in a volume of under one cubic meter at a weight of about 2,500 pounds at fuel efficiencies comparable to advanced vehicular diesel engines." (Koschier and Mauch, 2000)

The engine was designed for vehicular use where idle fuel efficiency is a concern. Land vehicles do not typically operate continuously at their maximum power so to optimize the turbine for fuel efficiency in lower power ranges the turbine required a recuperator. The LV100 as designed "burns about 25 percent of the fuel required for idling the T700," a simple cycle turbo shaft engine in the same power range as the LV100. (Koschier and Mauch, 2000) At over a ton lighter than comparable advanced diesel generators, Koschier and Mauch's description of a turbine generator based on the LV100 is very attractive, particularly as a prime mover for the DUKW 21.

Because of its many advantages, the LV100 has been selected to power the DUKW 21. The vehicle will see a broad range of power requirements, all the way from idle power during loading, to half power during land travel, to full power required to propel the ship at sea. The LV100 recuperated turbine, with its low idle fuel consumption, is well fitted for these operating conditions.

A single LV100 generator set, as described by Koscheir and Mauch provides more than enough power for the DUKW 21. The turbine is small, fitting well into an enclosure on one side of the hull above the waterline, with its air intake located high to ensure good clean flow. While the turbine is located off the centerline of the vehicle, it is light enough that it is not too difficult to counterbalance.

The LV100 has not been tested in the marine environment. Operating in maritime conditions could present complications for the engine, and the effect of these conditions on the engine should be investigated further. The engine does, however, boast a robust air filtration system, developed for operating in many environments, which could aid in an easier transition to marine operation.

Overall, the LV100 engine, coupled with an integrated high-speed generator, offers an ideal solution to the requirements of the DUKW 21's integrated electric propulsion system, and the vehicle as a whole.

Water Propulsor

Integrated podded motor propulsors were chosen for the DUKW 21's sea propulsion system. Waterjets and pumpjets were also investigated, but were found to present serious design complications that the podded propulsors did not.

Locating the waterjet and particularly the waterjet intake within the SWATH hull form proved to be difficult and inefficient. Waterjets are typically used in ships with more standard transom hull types. The pontoon of the chosen hull form tapers to a point toward the trailing edge and thus is not conducive to waterjet arrangements. Additionally, the tracks protruding from the bottom of the hull would likely prevent clean flow into the waterjet intake, which would have to be located directly behind the tracks.

A pumpjet would not require an intake, but pumpjets cannot vector their thrust as waterjets can. Differential powering alone would not likely provide suitable maneuverability, so rudders would need to be added to the design. It was determined that rudders should be avoided because they add complexity to the design and present a problem with ground clearance once the vehicle is on land. Finally, as with the waterjet, pump jets would require a motor within the pontoon, and space in the pontoon is limited due to the location of the tracks.

Podded integrated motor propulsors (IMPs) are ideal for the DUKW because they do not require rudders and are contained in a single pod, outside the hull. In this way they do not present arrangement difficulties by interfering with the track space.

Shaftless, rim-driven integrated motor propulsors from SatCon were chosen for their compactness and power density. SatCon has achieved a system power density of greater than 0.6 HP/lb in their propulsors. The rim-driven system has a reduced volume and weight and reduced mechanical complexity compared to shaft-connected systems. SatCon uses a Halbach array permanent magnet motor in their propulsors design, with the inverter integrated into the housing. A direct thermal sink to the outer shell cools the inverter. (“Revolutionizing USW Power Conversion,” 2007)

SatCon has already developed a rim-driven IMP to power UUVs, but they have not been developed to be azimuthing or retractable. Technology for fully azimuthing and retractable pods has already been developed however. Curtiss Wright Electro-Mechanical Corporation has designed pods for use in attack submarines as secondary propulsion units and they have already been implemented in the Seawolf and Virginia Class submarines. These pods are azimuthing and retract fully into the hull.

This technology has been implemented into the design for the DUKW 21. The ability to azimuth the pods eliminates the need for rudders. Also, the ability to retract the pods for land operation gives more ground clearance in the rear of the vehicle behind the tracks. This is illustrated in Figure 8. The illustration shows a simple mock-up for a hydraulic retraction system, but it is important to note that the propulsor suppliers would likely develop the detailed mechanical design for this system themselves.

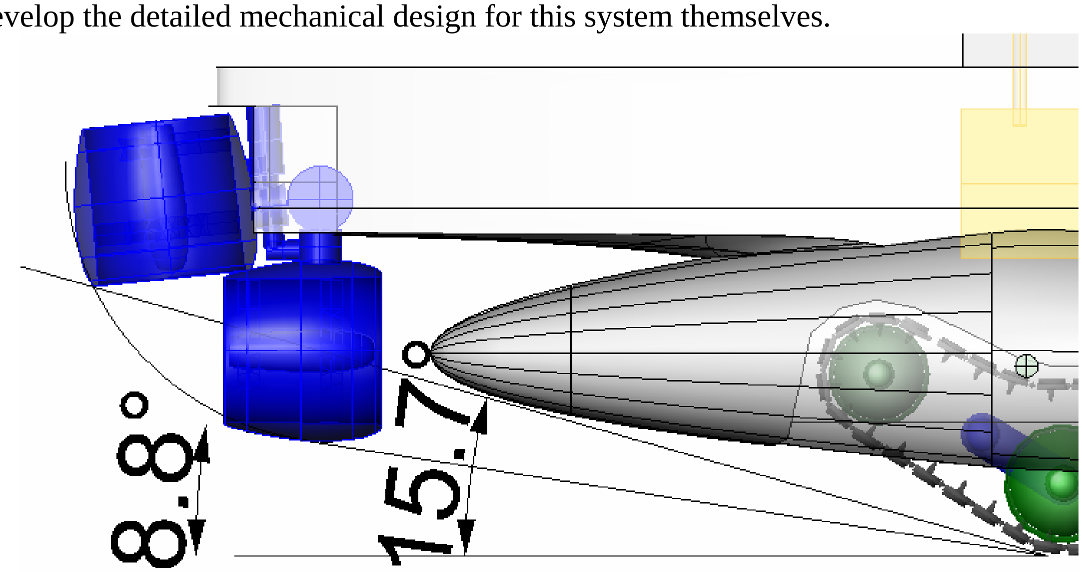


Figure 8: Retractable Propulsor Ground Clearance

In summary, the chosen water propulsion system for DUKW 21 consists of a rim-driven permanent magnet integrated motor propulsor, mounted underneath the aft overhanging section of the hull struts directly behind the pontoons. It is articulated through a mechanical retraction and steering strut. The diagrammed system above should suit the needs of the DUKW but to ensure the design is refined and it is effectively implemented more communication and cooperation with the suppliers is recommended.

Track System

Both wheels and tracks were considered for land propulsion for the DUKW 21. The advantages of wheels are that they are relatively lightweight, can move at higher speeds on roads than tracks, and are relatively simple in mechanical complexity. The advantages of tracks are that they have better capability to traverse broken ground and particularly soft ground with their expanded footprint. To insure that the DUKW 21 would be able to traverse most types of beaching environments, and because it was decided that the long narrow shape of a track system would fit better into the SWATH hullform, it was decided that the DUKW 21 would use tracks for its land propulsion system.

Track Design Requirements

An amphibious vehicle presents an interesting design challenge. A logical compromise must be established in order to create a vehicle that is capable of providing an optimized mix of performance on land and at sea. In order to minimize the drag in water, the vehicle needs to be long and narrow, which conflicts with land operation requirements. The maneuverability of a vehicle is affected by the ratio of the track length on the ground to the distance between the centerlines of the tracks. If this L/T ratio is less than 1.3, steering becomes unstable. If the L/T ratio is greater than 1.8 steering becomes difficult. The L/T ratio for the DUKW 21 is 1.72 which is within the envelope of acceptable values and also gives a slender layout which is favorable for decreased water resistance (AAAV design).

The size of the tracks has a very large impact on the SWATH hull dimensions and arched structure. The track width must be large enough to evenly distribute the vehicle weight in a marine beaching environment while maintaining a serviceable size. The ground pressure desired was around 56 kPa and required the DUKW to have a 0.53 m wide track.

	Dimensions
Track Ground Contact Length	9.30 m
Center-line Distance	5.40 m
Track Width	0.53 m
Vehicle Weight	56 m tons
Ground Pressure	56 kPa
L/T Ratio	1.72

Table 4: Track Characteristics

Track Configuration

The track system has been designed with one long track in each hull. A drive sprocket is at the fore end and an idling sprocket is at the aft end of each track, with 12 wheels per track. Two wheel motors drive each drive sprocket and they are positioned on either side of the sprocket.

The most prevalent feature of the track system is that the entire system is contained within a module that can be removed. This concept was developed to facilitate easier maintenance of the tracks. The tracks will be exposed to the marine environment and therefore corrosion will be a constant threat. Because of this it was determined that the tracks would need to be easily removed for maintenance. The concept for the modular track is that the entire track and suspension system and the drive motors will be contained in one unit that could be dropped directly out the bottom of the vehicle as shown in Figure 9. Bolts or some other clamping device will be used to secure the module to the hull, and electrical connections for the drive system will be at the fore part of the module, just above the drive motors.

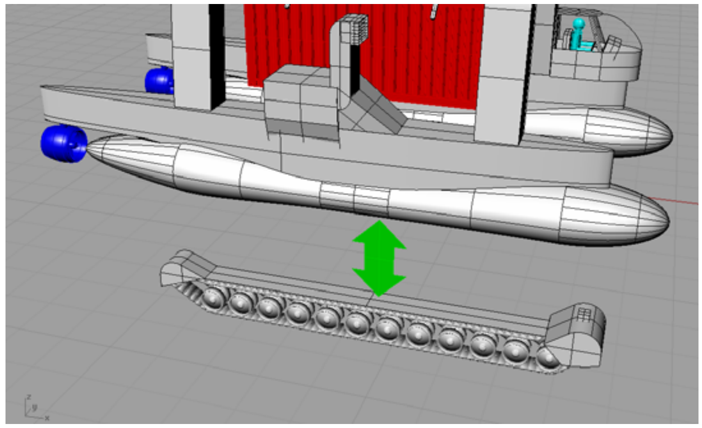


Figure 9: Track Module

Track Drive Motors

The motors used to drive the track systems require new state of the art technology from the automotive industry. Each pontoon of the DUKW contains an integrated modular track system that allows it to traverse on land. Since there is only a small amount of space available on each pontoon, the motors required for driving the track system needs to be compact and efficient. The PML Hi-Pa™ drive motor suits the needs of the track drive system. A photograph of the motor is shown in Figure 10.

These motors are wheel motors, designed for a high diameter but low thickness or profile. This “pancake” shape allows the motors to fit inside the hull. The key feature of this system is that it integrates the motor and drive electronics into one unit. This provides a revolutionary system that saves space inside the pontoons and is still able to supply the power required.

Figure 10: Hi-Pa™ Wheel Motor

Although the Hi-Pa™ drive motor was designed for use in commercial applications, the advantages it provides are well suited for the tasks needed in the DUKW 21. Wheel motors are designed to fit inside a vehicle’s wheels and drive the vehicle directly, without reduction gears or transmission. They are able to provide the high torque at low speeds that vehicles need to accelerate.

As shown in Figure 11, the track drive system has been designed so that two Hi-Pa™ motors drive each drive sprocket. The motors would be fixed and attached to an axle to drive the sprocket, rather than being integrated into the wheel as wheel motors are usually configured.

Also, the motors have been arranged just off the axis of the drive sprocket. In this way, the drive sprocket acts as a simple permanent reduction gear system. The motors were arranged this way so that they fit better into the hull, but also because the DUKW 21 is required to move at lower speeds on land than Hi-Pa motors are capable of, so speed was traded for torque.

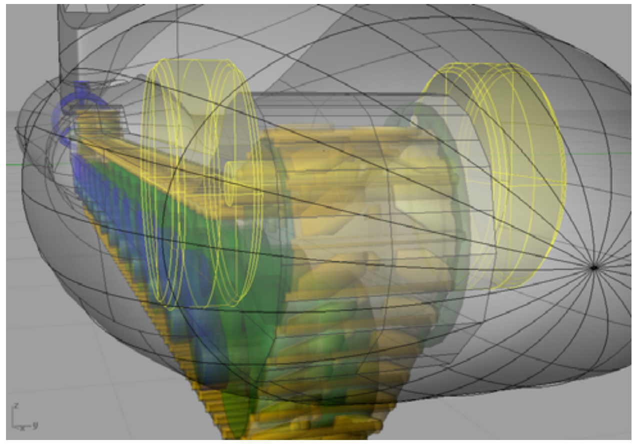


Figure 11: Hi-Pa™ Motor Placement

The current specifications for the Hi-Pa™ drive motor are displayed in Table 5 below.

	HPD40	HPD35	HPD30
Torque (max)	750Nm	500Nm	350Nm
Speed (max)	2000rpm	2000rpm	2000rpm
Power (max)	120kW	80kW	40kW
Mass	25kg	21kg	18kg

Table 5: Hi-Pa™ Drive Motor Design Characteristics

The performance of the motors was the most important factor in deciding to use the Hi-Pa™ drive. PML claims that the Hi-Pa™ drive has a power density 20 times greater than most conventional systems. It was calculated from the specifications shown above that the power density for these drives varies from 2.2 to 4.8 kW/kg.

Torque developed is another important factor in measuring the motor's performance. The largest motor listed develops 750 nm of torque and PML states that this torque remains relatively constant over the entire power range, dropping to about 600 nm at max speed. (PML Flightlink – Hi-Pa drive™)

While these performance numbers are very impressive, it has been calculated that in order to climb a three percent grade, the DUKW 21 would still need over twice the torque that four of the largest Hi-Pa™ drive motors can develop. It has been assumed that Hi-Pa™ motor technology could be scaled up to give the power and torque needed for the DUKW 21. The data shown above was extrapolated upwards to find a weight estimate for the DUKW's motors, and a 100% margin was added to that weight. Figure 17, showing the extrapolation, is contained in Appendix B.

Container Lift System

Introduction

The mission of DUKW 21 requires that the vehicle be able to load and unload a 20-foot ISO container autonomously. To best fulfill this requirement with a SWATH hull, DUKW 21 was designed so that the container would be lifted straight up and down from an arching cross structure. As designed, the lift system should give a high degree of flexibility when loading and unloading. During transit, the cables will be pulled tight to hold the cargo container secure and high above the ground and sea surface.

General Layout and System Components

Figure 12 illustrates the lift system layout with color-coding for ease of description. The spreader bar is hoisted up and down by four independently actuated cables, which are extended and drawn in by four winches (all shown in yellow). The cables are fed over pulleys, which are supported between transversely oriented beams (shown in blue). The pulleys are able to traverse the blue beams, so that the spreader bar can be moved transversely while the vehicle is stationary. The orange arrow in Figure 13 illustrates the direction in which the pulleys can move back and forth. The entire system is attached to longitudinal beams (shown in green in Figure 12), which are attached to the arches.

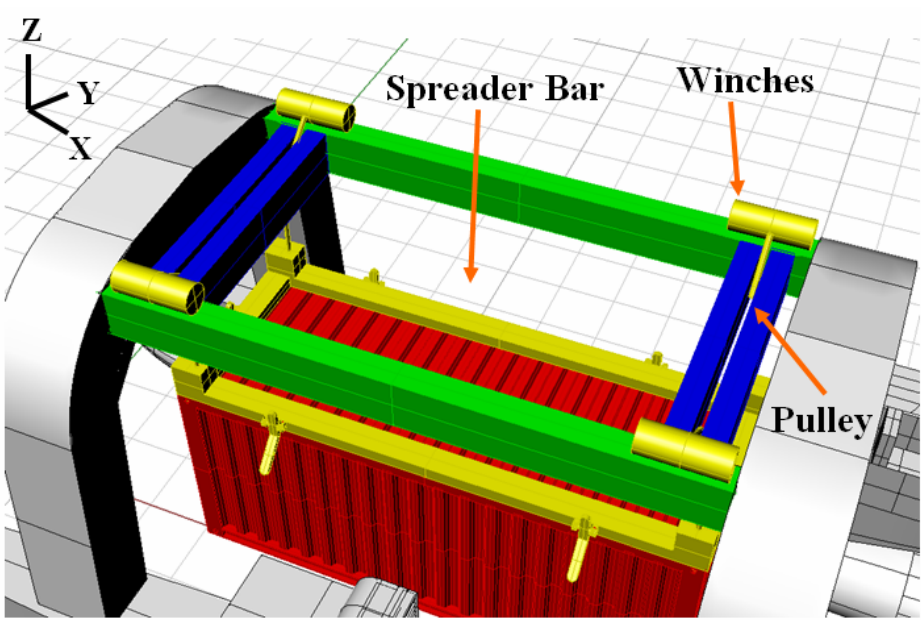


Figure 12: Lift System

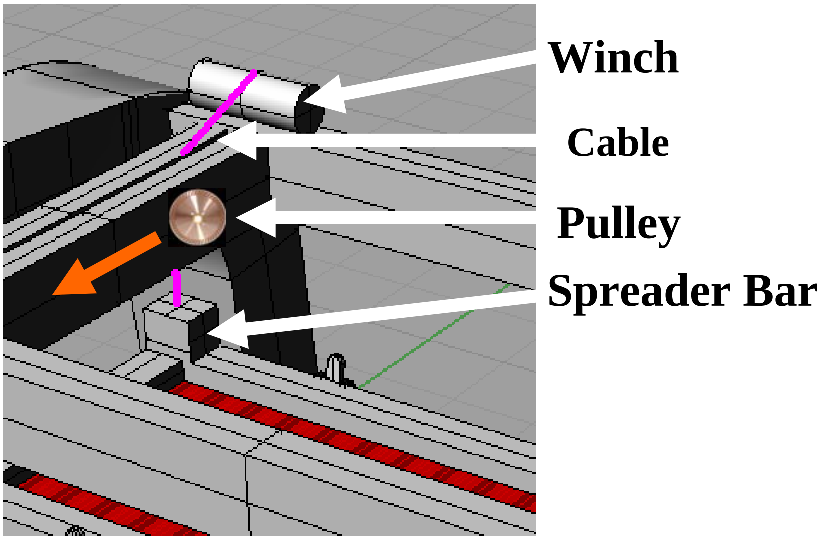


Figure 13: Lift System Components

Operational Capabilities

The design of the lift system gives the autonomous control system a great deal of flexibility in maneuvering the spreader bar. The autonomous system is able to maneuver the spreader bar in all six degrees of freedom. The first degree of freedom is the linear vertical movement of the spreader bar, which is achieved by hoisting the cables up and down. The second degree of freedom is a linear transverse degree of freedom achieved by the movement of the pulleys across the beams. The tracks of the vehicle provide the third and fourth degree of freedom, since the entire vehicle is able to move longitudinally and pivot about the vertical axis. The final two degrees of freedom can be achieved by hoisting the cables to different lengths, which would rotate the spreader bar about the transverse or longitudinal axes.

This system ensures that if the autonomous system is able to position the vehicle over the container, it can lift it. It simply drops the spreader bar onto the container, then the spreader bar locks onto the container, and the container is lifted back up. As an added measure, paddles attached to the spreader bar physically guide the spreader bar onto the container adjusting for any small misalignment.

The chosen lift system components fulfill the present safety requirements for marine lift systems. The factor of safety threshold currently used is 6 and the chosen components achieve a factor of safety of 6.7. The rigging chosen was one inch 316 Stainless Steel cable. This cable is salt water corrosion resistant and has a working load limit of over 89,500 lbs. The workhorses of the lift system are the four independently controlled Model c20 winches. These winches, each weighing only 650lbs, are capable of lifting nearly 20,000lbs (9,072kg) each, giving the system ample lift capability. (DP Winch Systems)

Autonomous System

Introduction

A fully autonomous system is a set of components that allows a vehicle to perform its task, after being programmed, without any aid from an operator. This section of the report will focus on broad concepts that will be needed to make the DUKW 21 completely autonomous. Specific systems and components will be avoided due to rapid advancements in the autonomous sector.

There are also many cases when an operator may want to take control of the vehicle. These cases include the vehicle not being able negotiate an obstacle, loss of traction in mud or other soft ground, and operation around other vehicles and personnel. For these cases the DUKW will need to be operable by remote or a one-person crew. Since remote operation technology for unmanned ground vehicles (UGVs) has already been proven by the military in a variety of roles, no direct focus will be given to remote control in this report.

Capabilities

Aside from the given requirements some basic assumptions were made to define a capable autonomous system. It has been assumed that the DUKW would travel on complex terrain including forests, deserts and urban settings. The DUKW's possible interaction with sandbars, however, is not addressed in this system. Also, the DUKW must be able to retrieve empty ISO containers for transport back to the ship.

For the DUKW to complete one complete mission it must perform the following tasks.

1. Pick up an ISO container from a ship
2. Disembark from the ship
3. Transit 5 nm to shore
4. Transition from water to land
5. Drive 5 nm inland
6. Drop off container in designated area, or at a specified point
   (Pick up empty ISO container, if required)
7. Drive back to shore
8. Transition from land to water
9. Transit to ship
10. Embark

Within these tasks the DUKW needs to have certain capabilities.

- Avoid obstacles on the surface of water, underwater, and on land;
- Track and avoid moving obstacles;
- Detect the location of the ISO container;
- Obtain relative position to ship, ISO container, and obstacles;
- Follow a predefined route;
- Interact with waves to stay on course; and
- Detect the shore and know when it's in water, on land, or in between.

Related Work

Many technologies are in development or have already been developed that can be applied to the DUKW's mission. The DoD has many autonomous vehicle programs already in place. Programs that apply to the DUKW 21 include the Defense Advanced Research Project Agency (DARPA) Grand Challenge and Space and Naval Warfare Systems Command (SPAWAR) unmanned surface vehicle (USV) projects. Private industry has also developed technology that can be applied to the DUKW including Simultaneous Localization and Mapping (SLAM), and Seiler International Corporation's AutoLog container handling system. Each of these projects and technologies are reviewed below.

DARPA Grand Challenge

One of the most publicized DoD autonomous vehicle programs is the DARPA's Grand Challenge. In 2005, a wide variety of teams entered DARPA's challenge to autonomously complete a 132 mile trip across the Mojave Desert. Four teams completed this trip in the ten-hour time period, and a fifth team completed the course outside of the time limit. The trip included complex terrain and various obstacles, but did not include moving obstacles aside from other competitors. This challenge directly relates to the DUKW project, because it proves that autonomous technology is mature enough for the land portion of the DUKW's mission. The vehicle of most interest was the fifth competitor to finish, Terramax, a vehicle from the Oshkosh team. While this vehicle is not as large as the DUKW 21, it is the largest completely autonomous vehicle currently in development. The Terramax was developed from an industrial vehicle that could carry a payload of 8,000 pounds. Oshkosh is undertaking measures to make Terramax's successor available to the military. (Lawlor, 2006)

The navigation method used by DARPA is also significant to this project. The DARPA Grand Challenge had a comprehensive mapping system, involving GPS waypoints for navigation. Two hours before the start of the race each team was given what is called an RDDF. The Route Definition Data File is a text file containing a series of numbers separated by commas. Each data point was five numbers long. An Example:

1	38.2228914	-110.4790771	20	10
2	38.2224215	-110.4793187	20	55
3	38.2216479	-110.4799700	30	55

The first number is the order in which the data points are to be followed. The second and third numbers correspond to the latitude and longitude of the waypoint, respectively. The fourth number is the Lateral Boundary Offset Number (LBO). The fifth number is the maximum speed allowed between waypoints, imposed as a safety measure. "The lateral boundary offset (LBO) is the distance in any direction from the track line (including a radius at the end points) that defines the corridor in which vehicles are permitted to travel. The width of this corridor will vary according to safety, environmental, and passing considerations." (DARPA, 200-7)

Unmanned Surface Vehicles

SPAWAR has recently taken up the project of creating an USV. Their purpose is as follows; "The US Navy and other DoD and Department of Homeland Security (DHS) organizations are increasingly interested in the use of USVs for a variety of missions and applications. In order for USVs to fill these roles, they must be capable of a relatively high degree of autonomous navigation. SPAWAR is developing core technologies required for robust USV operation in a real-world environment, primarily focusing on autonomous navigation, obstacle avoidance, and path planning." (SPAWAR, 2007) Another project performed at SPAWAR was on a small robotic convoy. Both projects were evaluated for relevancy to the DUKW 21.

The Naval Surface Warfare Center, Carderock Division (NSWCCD) has been testing two USVs at Ft. Monroe. The two vehicles are to help with the missions of a littoral combat ship. (Burgress, 2006) The USVs can navigate using either GPS waypoints or only a final destination and each has the capability to avoid moving obstacles and even swimmers in the water. The NSWCCD test facility plans to conduct a completely autonomous mission within the year. The DUKW 21 is too different in size and hull shape for direct system transfer, but all of these USVs use technology that would be applicable to the DUKW 21, and the general philosophies of the current USVs can be applied to the DUKW 21 autonomous system design.

Localization and Mapping

ISO Lifting

System Overview

The autonomous system is composed of smaller components integrated together. This section delivers an overview of the overall system prior to definition of the smaller components in later sections.

In order to achieve this autonomously the DUKW has several requirements for sub-systems that will provide autonomous control and limited intelligence for aspects of the overall mission. These requirements are:

Mission Related System Components

- The autonomous system needs a command system to integrate the demands and signals from the sub-systems to allow for conflict resolution between competing demands.
- The DUKW needs systems that enable it to reliably locate the ISO container to lift it. At the delivery point the DUKW will need to place its ISO container at a specified point. ISO localization can be broken down into two main parts; locating the ISO container in the global reference frame, then having the DUKW move itself to appropriately lift the ISO container.
- The DUKW requires systems to counter the impact of a moving ship and a seaway when the DUKW is to disembark from the ship
- On both land and sea the DUKW requires positioning and navigation systems, most likely including a mapping component and sufficient intelligence to interpret the mapping component to allow physical obstacles to be avoided. Within the mission, the DUKW will need to cross the surf and beach zones. The navigation system would include its location in reference to obstacles, specified targets such as the ISO container and the ship, as well as its global position for mapping purposes.
- Each of these components will be in use at separate time intervals therefore will not need to interface with each other.

- The final consideration is a human system operator. If remote control or one manned control is performed in conjuncture with the autonomous system then the operator needs to be integrated into the command system.

Maintenance System Components

- The Internal System Maintenance Component will monitor engineering system performance, reduce system loads to prevent damage and develop preventative maintenance requirements.
- Within the Shore Interaction Component the DUKW will be able to sense the shore is approaching, be able to calculate the water depth to know when the tracks should be turned on, and decide when the water is at the right level to turn off the water propulsors.
- The Obstacle Avoidance Component will protect the DUKW from damage by foreign objects in its environment.
- The Operator. It is important to note that the autonomy will only be used where the mission requirements allow. In particularly harsh terrain and when the mission is particularly critical and difficult, a human operator will perform the mission.

Component Hierarchy

For these components to act as a system, a decision making hierarchy will be set for proper completion of mission tasks; the hierarchy will be influenced by the interaction level of an operator. The human operator, if implemented, will have final decision on all matters. The operator's influence can extend from basic monitoring of the DUKW to remote operation to complete and direct control of the vehicle.

Remote operation will require access to the data provided by the sensor components of the other autonomous components as decision aids. This data would inform the operator on what course should be taken, when obstacles are in the area, and of any direct or relative positioning information. In this case the DUKW's decision-making components will be passive.

A more complex management and control hierarchy is required for completely autonomous operation. Mission components will be the main drivers during the cargo to shore operation. Maintenance and protection of the DUKW will override all mission components in decision-making. For example if while completing tasks, an obstacle is detected or there is an internal error, the resulting decision will be to immediately avoid the obstacle or correct the error.

Navigation Systems

The DUKW 21 will need to have both passive and active sensing capabilities to find its way to the final location. Passive methods would include incorporating a pre-set route towards the drop off location and using data collected from previous trips to update the preset route. Active methods would use sensors to detect obstacles and create landmark features to stay on course.

Mapping; Passive Sensing

For mapping purposes the GPS unit will be used. Implementing the waypoint navigation used by DARPA and adding a sixth number corresponding to terrain would give the

DUKW a line to follow from ship to shore. Terrain classification, the sixth number, would let the DUKW know what sensors need to be activated at certain times, to save power and to prepare for transition from water to land.

Assuming the DUKWs will be arriving on shore after an initial amphibious landing force, these navigation numbers could easily be set by elements of the landing force as they drove towards their destination. The vehicles used to obtain these navigation data points could include landing vehicle and the ground vehicles they carry, another amphibious vehicle, or an initial DUKW driven by an operator. The mapping vehicle would need to travel on a direct course to the cargo drop-off area. As the mapping vehicle made its way, the navigation points would be compiled from GPS way points taken at predefined distance intervals, the speed of the vehicle, and simple input from the personnel defining the terrain classification. This pre-mapping method would allow for less computation by the DUKW and a known secure passage to travel.

Obtaining the LBO may not be feasible for the land force. This number is not critical to the DUKW because it can use its active sensing in travel to stay on course, but the LBO could be created as a DUKW moves along during its first trip for information on successive trips.

A straight line is not always a feasible route for a vehicle to travel; therefore a path will need to be created. To do this the SLAM algorithm will be used. Using sensor information a 3D map will be made giving the DUKW its passable route and offset boundaries. Another advantage of creating this 3D map would be to allow to DUKW 21 to locate its position by landmark identification if the GPS system is not available.

Obstacle Avoidance; Active Sensing

Once the DUKW 21 has a set path to travel, it will need to be able avoid obstacles. Active sensors will be used to detect possible threats to travel and allow the DUKW to either move around, or stop and change its course.

Sensor Suite

Light Detection and Ranging, commonly called LIDAR and laser detection and ranging (LADAR), are sensing techniques that use light to detect ranges from targets. LIDAR will be used in a passive sensing role for Mapping and DUKW Localization and in an active sensing role for Shore Interaction and ISO Localization.

A Stereo Camera is a type of camera that uses two lenses to capture a 3D image. This can be used in juncture with LIDAR for better 3D mapping, ISO handling, and ship docking. Stereo cameras will also be used with IR sensors for active detection of obstacles, specifically moving obstacles, and people.

For sensory information in the water, multi-beam sonar will be implemented. Multi-beam sonar gives a ‘fan-shaped’ view of the water below the vehicle. This will be used for depth sensing and underwater obstacle avoidance.

For waypoint matching a GPS unit will be implemented, and an inertial navigation unit will be used for relative positioning. If there were an instance in which the GPS system went down, the inertial navigation unit would be used in conjuncture with other the other sensors to stay on course.

The DUKWs will need to be told what ISO container to pick up. This can be done through a number of marking systems, but investigation into these methods has not been performed in this report.

Weight Breakdown

For the DUKW 21 weight summary, the subsystem weights were organized into categories based on primary function and role. The SWBS system was determined to be impractical for the DUKW 21 weight breakdown. Because of the amphibious nature of the vehicle and its mission, much of the vehicle's critical systems, such as the track drive system and the container lift system, would not fit into the traditional categories of the SWBS system and would have to be accounted for as auxiliary systems. Therefore, the weight breakdown system shown below in Table 6 was created to replace a SWBS weight breakdown. A detailed weight breakdown is included in Table 14 of Appendix B.

Item	Estimated Weight (kg)	Adjusted Weight (kg)
Hull and Frame	8,740	9,725
Power Pack and Drive Train	3,604	4,275
Suspension, Tracks, Steering	10,800	12,420
Fire Control	90	99
Autonomy and Control	136	163
Bilge System	120	132
Container Dismount System	2,680	3,039
Total Unloaded Weight (14.1% Margin)	26,170	29,853
Payload		
20 Foot ISO Container	24,000	24,000
Fuel (10 Trips, 5% margin)	2,382	2,501
Total	26,382	26,501
Total Vehicle Weight	52,552	56,354

Table 6: Weight Breakdown

The "Estimated Weights" shown in table 6 are totals of the best estimates for each item in that category. The "Adjusted Weights" reflect the totals of the individual items under each category after a margin has been applied to each item. The displayed unloaded margin reflects the difference between the unloaded estimated weight total and adjusted weight total, rather than an arbitrarily imposed margin on the estimated unloaded total. It was decided that applying margins to individual items was best because at this conceptual stage of design, confidence levels in individual item estimates very greatly. The margins for each item are displayed in the detailed weight breakdown in the Appendix.

Weights for each item were estimated with different methods. For most items under "Hull and Frame," weight was estimated by finding the surface area of the item using the Rhino 3D model, then multiplying by a thickness and density (Aluminum, 2.7 tonne/cubic meter) then adding 30% for stiffeners. Fuel weight was estimated by calculating fuel consumption for each stage of the DUKW's mission. For most other items in the weight estimate, weights were either transferred directly from existing equipment, or scaled from existing equipment.

Summary

Design Summary

The DUKW 21 final design is a tracked SWATH ship outlined by the characteristics and capabilities shown in Table 7.

	Metric	English
Length	16.05 m	53 ft
Width	7.62 m	25 ft
Height	7.28 m	24 ft
Weight	56,354 kg	124,239 lbs
Cruising Speed	15 knots	17.26 mi/hr
Output	1 MW	1,500 hp
Range	200 nm	230 mi
Cargo Capacity	24,000 kg	52,911 lbs
Cargo %	42.6%	

Table 7: Final Design Characteristics

The DUKW 21 is an amphibious vehicle that has well-balanced performance on both sea and land. By providing a new capability in cargo transfer, it could drastically improve the logistical and tactical performance of the United States' Armed Forces. The vehicle incorporates today's latest technology to fulfill the design requirements. After the team's initial analysis it is believed that there is a viable solution to the mission requirements with today's technology and it is recommend that the DUKW 21 concept be developed further.

Risk Assessment

There are several areas of certain risk associated with the DUKW 21 concept. As the design is carried forward, these risks must be minimized by focused research and development. To convey this idea a system of risk identification was created and it is illustrated below in Tables 8-11.

Severity	Threat to feasibility of current design
Catastrophic	Design-ending failure. Requires complete overhaul of DUKW 21 design.
Disastrous	Major system design overhaul. Replace components with much difficulty.
Critical	Requires major, but feasible design change
Significant	Requires small change in design
Marginal	Small loss in performance of vehicle but no redesign necessary

Table 8: Severity Categories

Likelihood of failure	Description
Very likely	Unproven, untested, theoretical technology. Low confidence in technology.
Likely	Technology is new or under development, questionable and has not been tested.
Possible	Technology is new or under development, but looks promising and has been tested.
Unlikely	Technology is unlikely to fail. Only a slight modification from proven technology.
Proven	Technology is proven or off-the shelf. Failure is remote.

Table 9: Probability Categories

	Very likely	Likely	Possible	Unlikely	Proven
Catastrophic					
Disastrous					
Critical					
Significant					
Marginal					

Table 10: Risk Categorization

Item of Concern	Probability	Consequence	Assessment
Hull Resistance	Possible	Critical	
Propulsor efficiency	Very Likely	Significant	
Damaged Stability	Possible	Disastrous	
Scalability of Hi-Pa	Unlikely	Significant	
Track System	Very Likely	Disastrous	
GE LV100 turbine	Unlikely	Marginal	

Table 11: DUKW 21 Risk Assessment

Hull Form Resistance

Resistance for the DUKW 21 has been calculated using computer analysis tools and simple additions for appendage drag due to the tracks. It is likely that model testing will reveal that the resistance on the vehicle is different than the computer analysis indicates, but the degree to which the actual resistance differs is hard to predict.

If the resistance is only 10% greater than what is currently predicted, it is possible that the current power plant is still suitable and no change to the design is necessary. However, if the resistance is more than 20% greater, additional power would be needed to reach the design cruise speed. This could be achieved by simply placing a second LV100 turbine generator set on the port side of the vehicle, or by selecting a different primary generator. Also, the previously cited article by Koshier and Mauch states that the LV100 could be scaled up with the current technology to a higher power output. For a drag increase in the range of 20%, scaling the LV100 would probably be the best option. For an increase greater than 50%, adding a second turbine or selecting a different generator set would probably be the best option. Additional fuel would be required in any case, and therefore the vehicle's weight could increase significantly.

It has been determined that it is "possible" the DUKW 21 will produce much more drag (more than 20%) than expected and this event would be a "critical" threat to the design. This means that greatly increased drag is a "yellow" level risk. It is therefore recommended that model testing be conducted upon further work on the vehicle.

Propulsor Efficiency When Not Fully Immersed

Under the current design's unloaded condition, the podded propulsor is not fully immersed. This can decrease propulsive efficiency, but amount of efficiency lost has not been determined. If the loss in efficiency is significant, changing the propulsor's retracting strut so that the pod is fully immersed when extended could solve the problem. This would mean some moderate change in the strut's weight or complexity.

The likelihood of this threat has been determined to be "very likely" but the severity has been deemed only "significant." Therefore, this is a "green" level risk. It is recommended that more work be done with propulsor suppliers to determine how the propulsors would perform in the current design, and how the retractable strut could be constructed to alleviate the problem.

Damaged Stability Analysis

Thus far, only intact, static stability has been investigated for the DUKW 21. While the results of this analysis show that the DUKW 21 should be a very sturdy vehicle, dynamic stability and particularly damaged stability has yet to be assessed. The DUKW 21's weight estimate accounts for watertight bulkheads. Still, because this is a new type of vehicle, the damaged stability analysis may show surprising results.

This threat has been determined to be of "disastrous" consequence severity and it is "possible" that the damaged or dynamic stability is not suitable, so the risk level is "yellow." It is recommended that damaged and dynamic stability analysis be conducted for the DUKW 21 as soon as possible upon further development of the project.

Scalability of Hi-Pa™ Drive Motors

PML's wheel motor technology is very promising, but they have yet to produce a Hi-Pa™ motor in the range required for the DUKW 21. It is "unlikely," however, that the motor technology could not be scaled to the power needed for the DUKW 21, and even then, different motors could be selected without much difficulty. Therefore, the threat to the design is "significant." This risk is therefore a "green" level risk. This aspect of the design should be firmed up, but is a low level priority.

Track System Corrosion and Serviceability

Failure of the track system would be "disastrous" and because there has been minimal development of the modular concept, the likelihood of failure has been determined to be "very likely". This is therefore an "orange" level risk. It is strongly recommended that this system receives a high priority and be developed to a suitable level of confidence immediately upon furthering of the DUKW 21 project.

Conversion of the GE LV100 Turbine for the Marine Environment

The LV100 gas turbine was developed for use in land vehicles, and although it was designed to withstand the harshest land environments, it would need to be adapted for marine use before being installed in the DUKW 21. This conversion would not likely add much weight to the turbine, and is therefore not a significant threat to the design. It is therefore a "green" level threat and can receive a low priority in development.

Bibliography

AAAV Design. Advance Amphibious Assault Vehicle Final Report Vol. 1 section 3-3 hull length

A New Generation. Richard R. Burgess. Navy League of the United States, July 2006. http://www.navyleague.org/sea_power/jul06-26.php

AutoLog; Automated Container/Cargo Transfer. Seiler International Cooperation, July 26th 2007. http://www.seicor.com/

DEMO III / Experimental Unmanned Vehicle (XUV). Global Security, July 26th 2004. http://www.globalsecurity.org/military/systems/ground/xuv.htm

DUKW in Action. Glocal Security. July 26th 2007. http://www.globalsecurity.org/military/systems/ground/dukw-action.htm

DUKW. U.S. Army Transportation Museum, July 26th 2007. http://www.transchool.eustis.army.mil/Museum/DUKW.htm

DP Winch Systems. Industrial Winches
http://www.team-twg.com/DpWinch/PlanetaryWinchDetails.aspx?Company=DP+Winch&Category=Planetary&Type=Winches&ProductId=C20&DpCategory=Industrial

General Dynamics Document number G9-90-23272-D. February 1991
MCPO # 002663 Drawer 84

Intelligent behaviors for a convoy of indoor mobile robots operating in unknown environments. Nathan M. Farrington, Hoa G. Nguyen, Narek Pezeshkian. SPAWAR Systems Center, SanDiego. Robotics Update, 2004, Vol 4.

Koschier, Angelo V. and Hagen R. Mauch. (2000). Advantages of the LV100 as a Power Producer in a Hybrid Propulsion System for Future Fighting Vehicles, *Journal of Engineering for Gas Turbines and Power*, 122, (4), October, 693-698.

LARC Lighter, Amphibious, Resupply, Cargo. Global Security, July 26th 2007. http://www.globalsecurity.org/military/systems/ship/larc.htm

LVTP7 Landing Vehicle, Tracked AAVP7A1 Assault Amphibian Vehicle Personnel. Global Security, July 26th 2007. file://///Cisd11/cisd%20share/2-CONCEPTS/Projects/FY07%20Projects/DUKW21%20&%20USV%20(ISO%20Cargo%20to%20shore)/2-Research/DUKW%20Links/Other%20Amphibious/Assault%20Amphibian%20Vehicle%20Personnel%20Model%207A1%20(AAVP7A1).htm

MARINE AMPHIBIAN TRUCKS (DUKW - "Duck"). Arthur W. Wells. July 26th 2007. http://members.aol.com/twodukw/twodukw.htm

PML Flightlink – Hi-Pa drive™. 2007. http://www.pmlflightlink.com/motors/hipa_drive.html.

Real-Time Simultaneous Localization and Mapping with a Single Camera. Andrew J. Davison, ICCV 2003. http://www.doc.ic.ac.uk/~ajd/Publications/davison_iccv2003.pdf

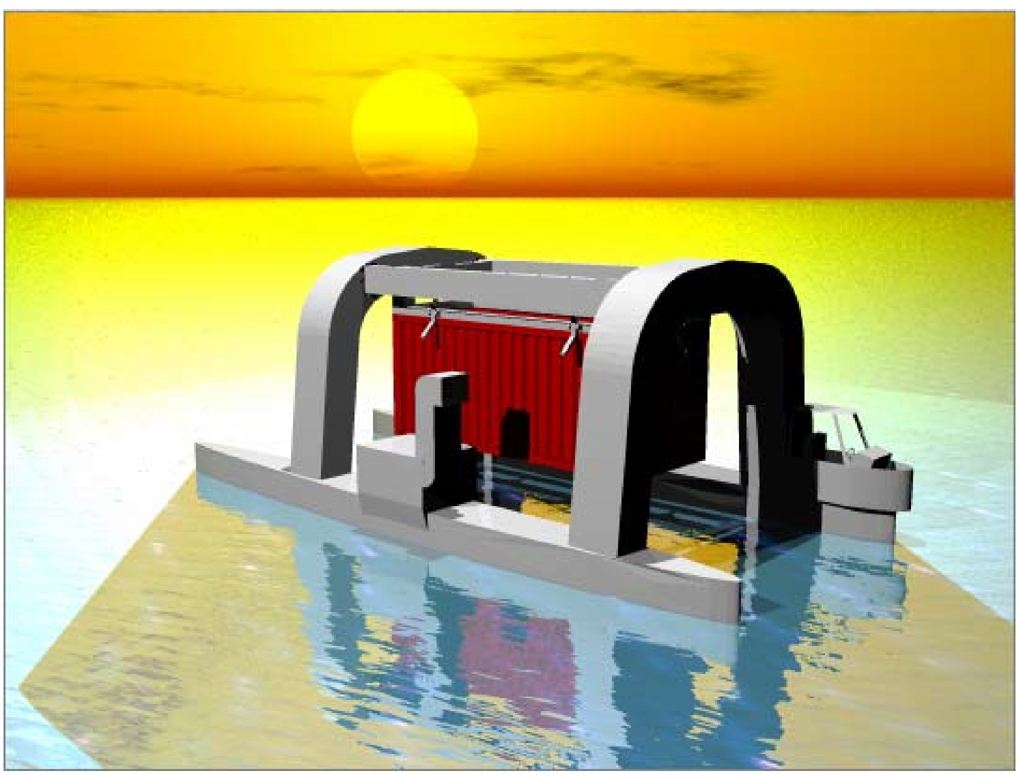
Revolutionizing USW Power Conversion [Brochure]. (2007). Boston, MA: SatCon Applied Technology.

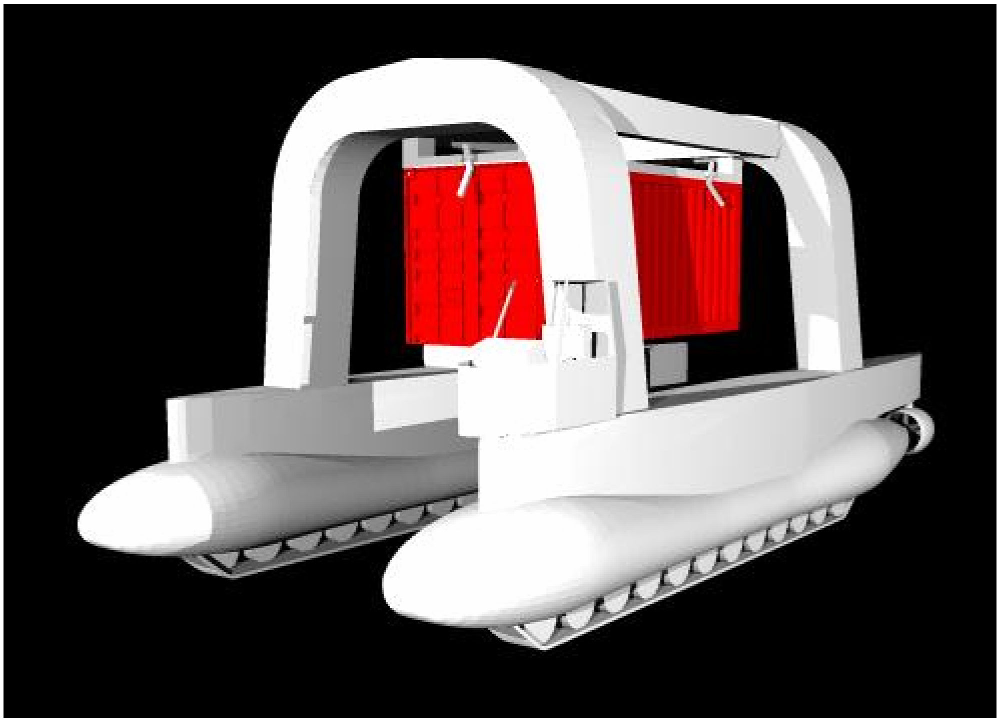
*Unmanned Ground Vehicle Struts Its Stuff***.** Maryann Lawlor. February 15th 2006. http://www.imakenews.com/signal/e_article000524385.cfm?x=b11,0,w

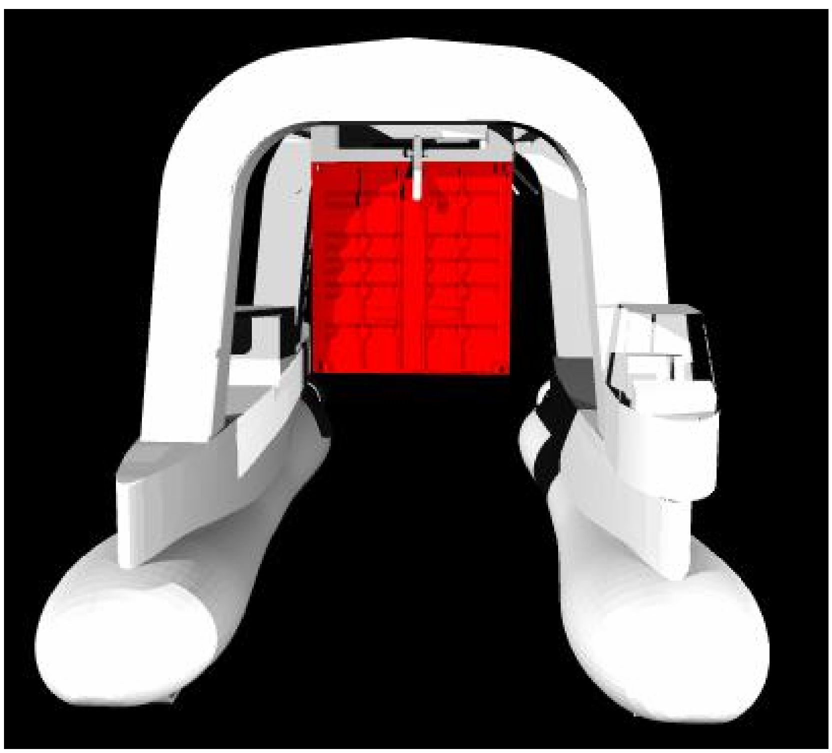
Urban Challenge Rules. DARPA Grand Challenge, July 26th 2007. http://www.darpa.mil/grandchallenge/docs/Urban_Challenge_Rules_071007.pdf

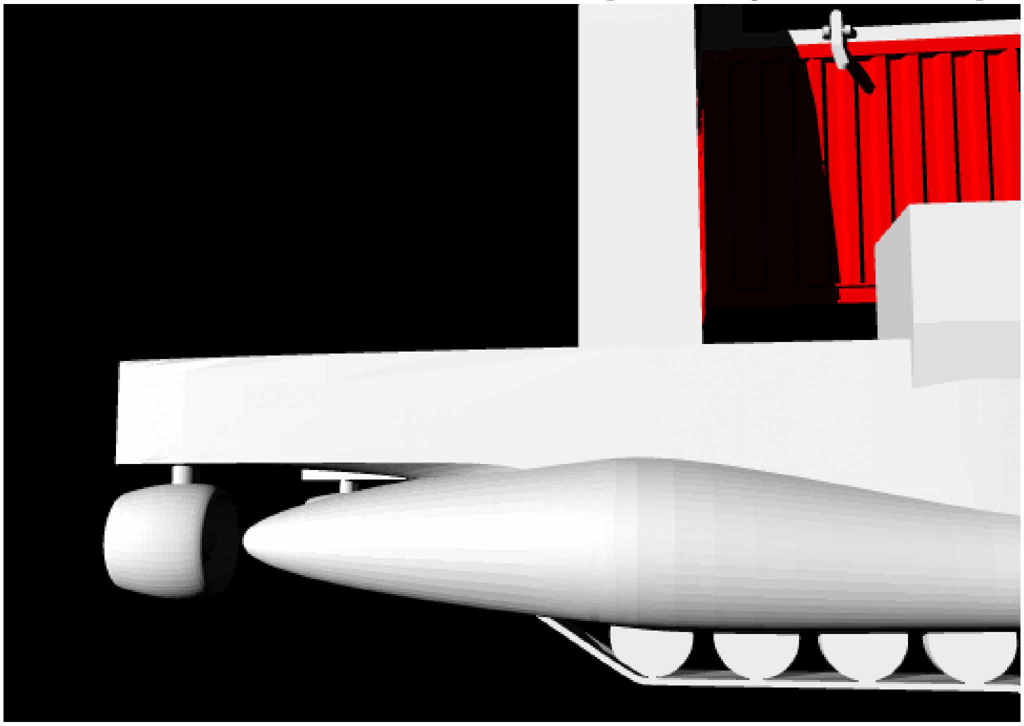
Wire Rope. Sanlo lift components. http://www.sanlo.com/product/gswire.htm.

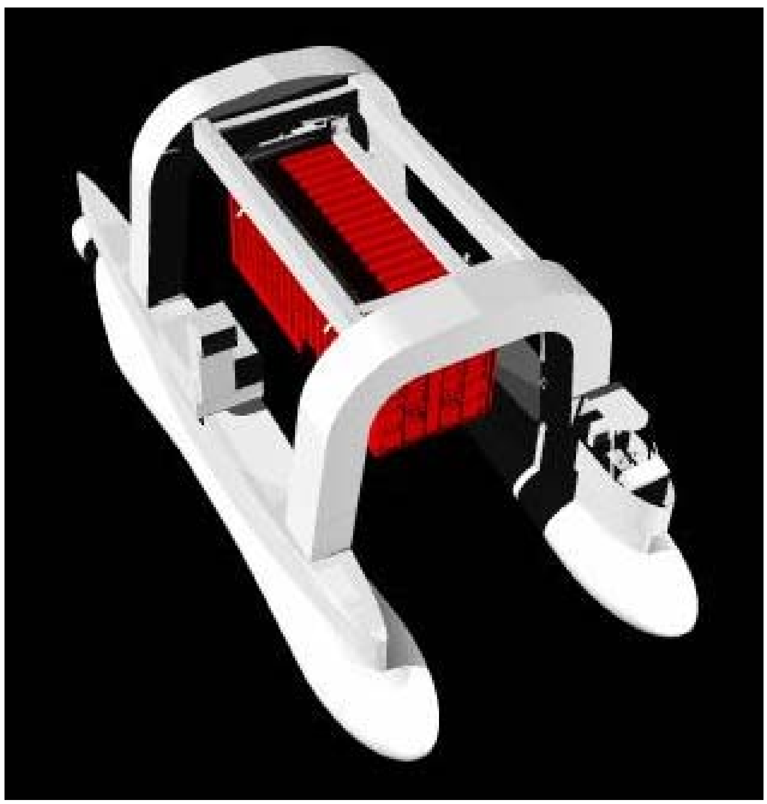
Appendix A: Images

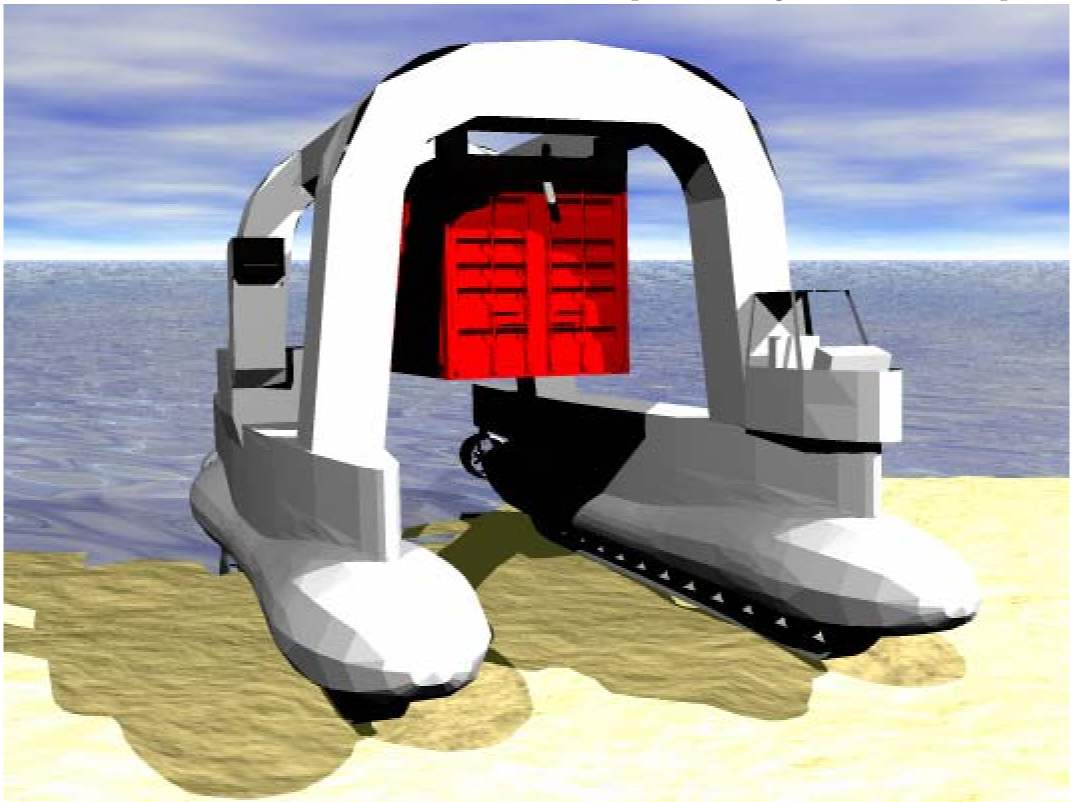


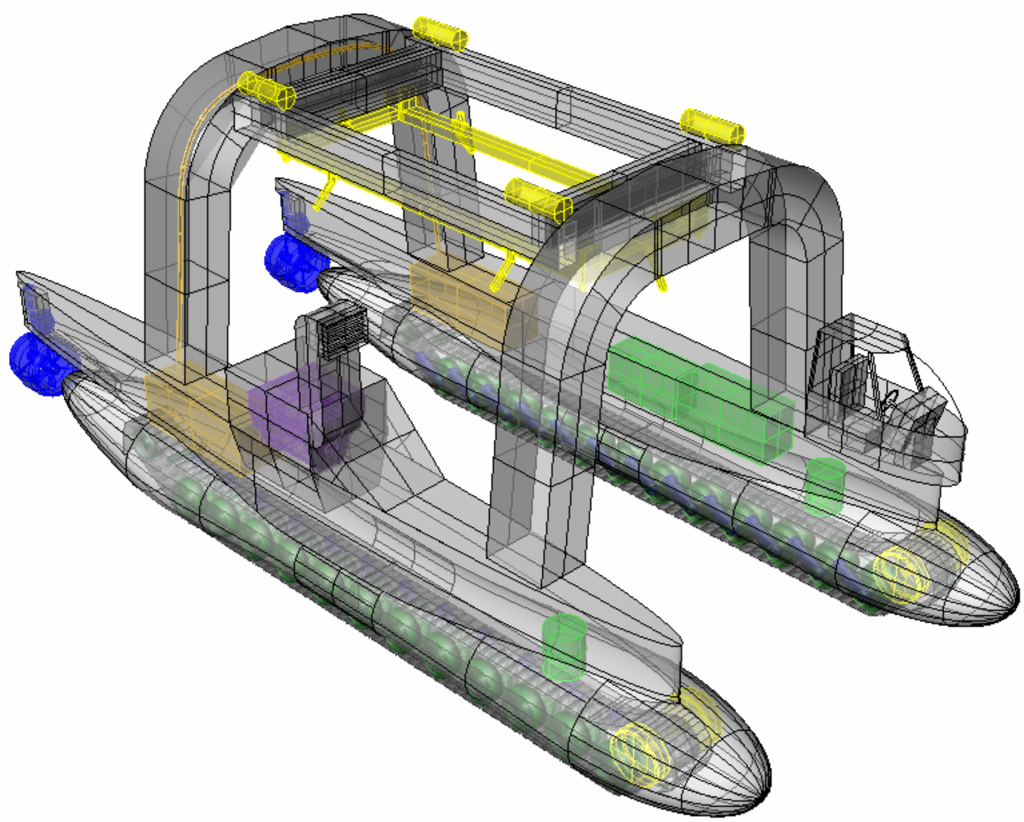


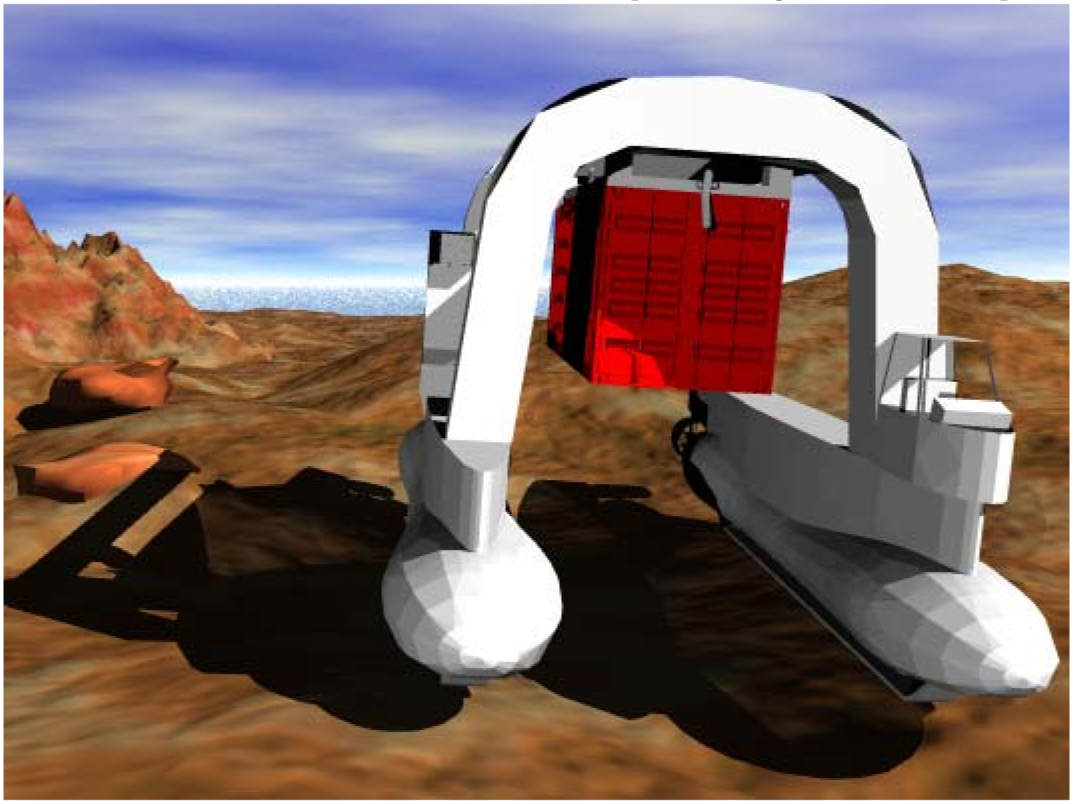












Appendix B: Supporting Calculations

	A	B	C	D	E	F	G	H	I	J	K
1	**Deck height**	0		**Deck 1**			**Deck 2**			**Beam**	
2	**Hull height**	1.33		Length	0		Length	0		Amount	2
3	**Draft**	1.693		Thickness	0		Thickness	0		Length o	1
4	**Height Bdeck**	0.4835	1.788	Area	0		Area	0		Height o	0.8
5	**Height Adeck**	9		Y1	0		Y2	0		Thickness	0.001
6	**Neutral Axis**	8.6								Length I	0.998
7	**Moment arm**	9.0835								Height I	0.798
8										Area per	0.003596
9	**Displacement (LT)**	1,524								Area total	0.007192
10	**Length (ft)**	279			**Id1**	0				Y3	8.6
11	**Draft (ft)**	12.1			**Id1pa**	0					
12											
13	**Length/Draft**	23.06			**Id2**	0					
14	**Parameters**				**Id2pa**	0					
15	*t*		*1.051*								
16	**T**		0.559		**Ib**	0.000404					
17	*Le*		*24.244*		**Ibpa**	0.000404					
18	*Length Tanh function*		*0.766*								
19	**L**		1.564		**It**	0.000404					
20	*Displacement Tanh function*		*0.138*								
21	**D**		1.452								
22	**Side Force/Displacement**		0.927		**Element**	**Bending Stress (Pa)**					
23	**Side Force (LT)**		1,413		Deck 1	2.63E+12					
24	**Metric Tons**		1384.4914		Deck 2	2.63E+12					
25	**Side Force (N)**		13581860		Beam	1.22E+11					
26											
27	**Moment (N*m)**		123370827								

Table 12: Arch Structure Stress Calculations

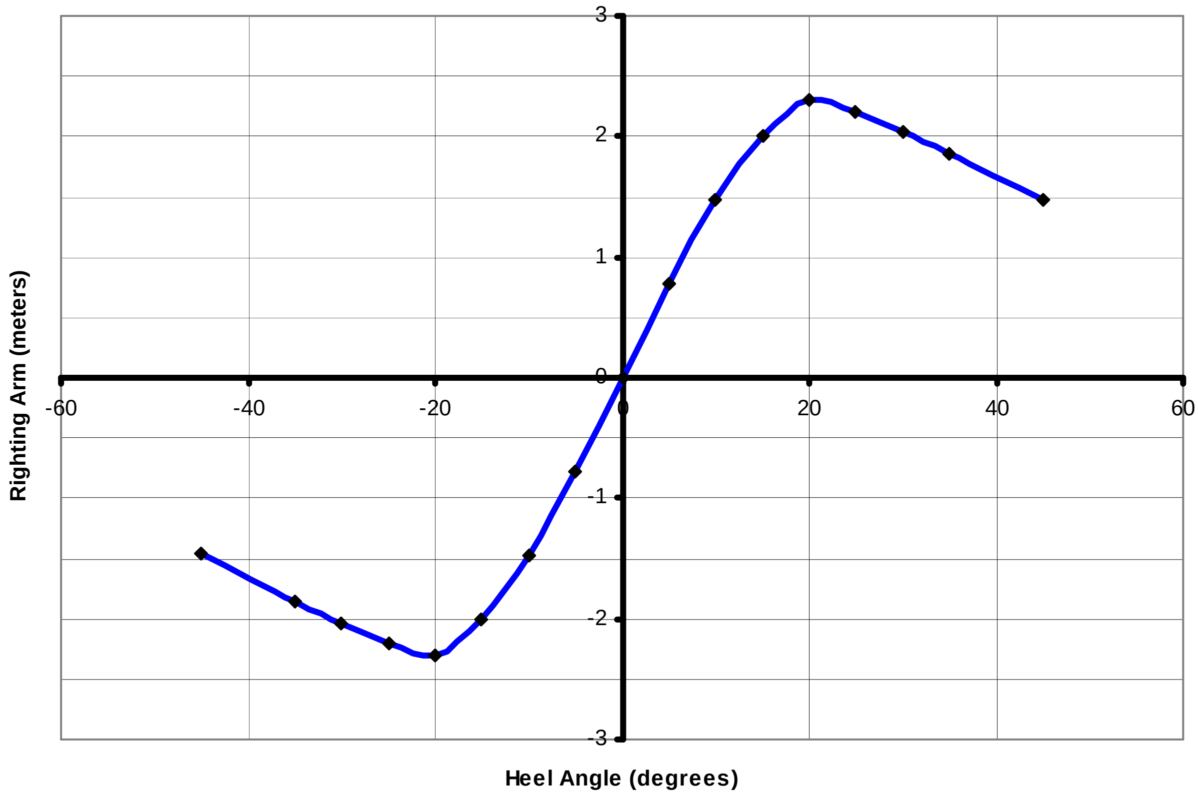


Figure 14: GZ Curve for the Unloaded Condition

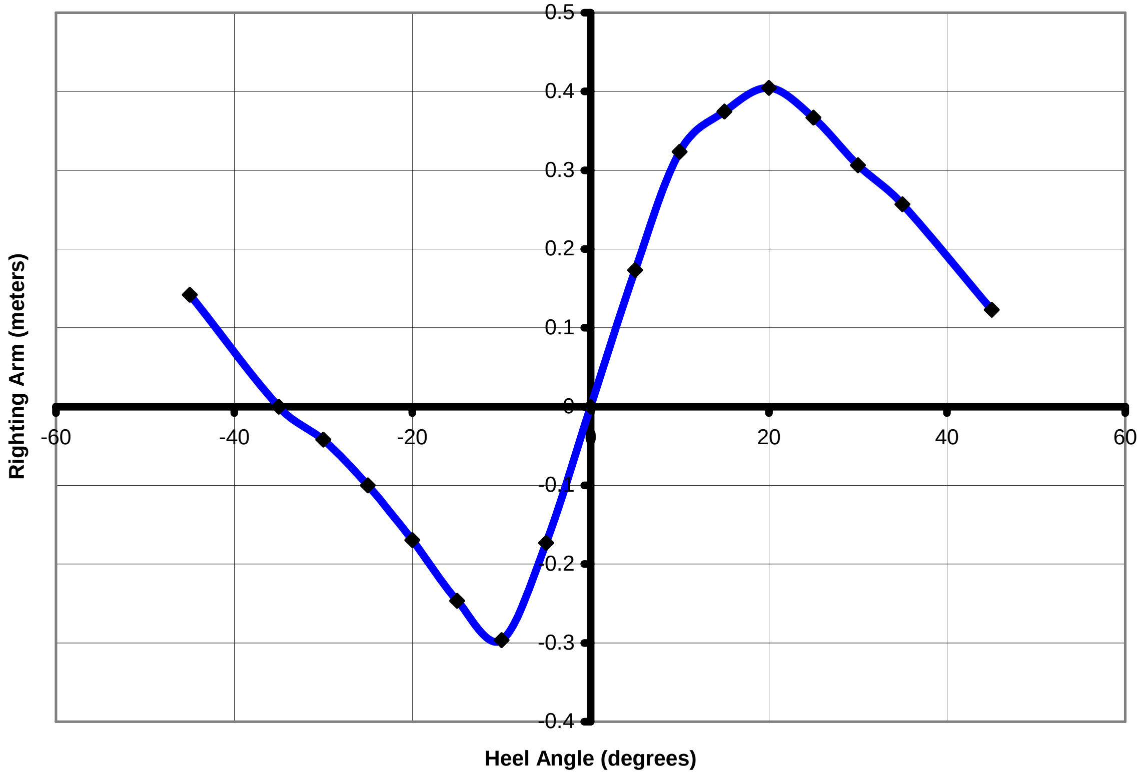


Figure 15: GZ Curve for the Loaded Condition

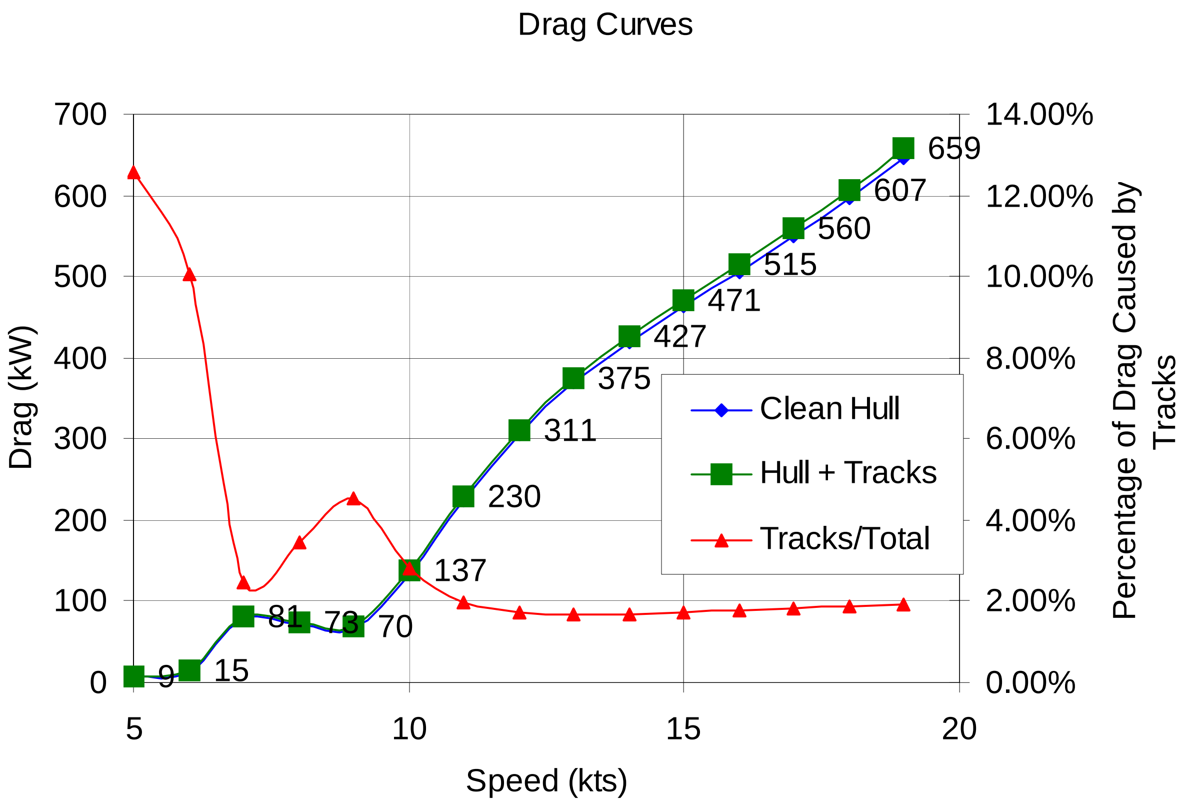


Figure 16: Drag Curves for DUKW 21 at Loaded Condition

The blue and green lines show the effective horsepower required for a given speed, and the red line shows the percentage of drag added to the clean hull drag by the tracks.

Power Inventory (kW)						
Power Input	**Loading**	**Traversing Water**	**Traversing Land**	**Unloading**	**Return on shore**	**Return on water**
Water Propulsors (2)	0.0	860.0	0.0	0.0	0.0	851.0
Hi-Pa Motors (4)	0.0	0.0	400.0	0.0	400.0	0.0
Winches (4)	70.0	0.0	0.0	70.0	0.0	0.0
Autonomous	2.5	2.5	2.5	2.5	2.5	2.5
Total	**72.5**	**862.5**	**402.5**	**72.5**	**402.5**	**853.5**

Table 13: Power Requirements of Major Systems

The main power drawing components of the DUKW 21 vehicle are the integrated motor propulsors, the Hi-Pa motors, the ISO container lift system and the autonomous control systems. Assuming a propulsive efficiency of only 60%, it has been calculated that the water propulsion system would consume about 860 kW at 16 knots while cruising to shore, and about 850 kW at 15 knots returning to the ship.

The power required for the container lift system was estimated by calculating the work required to lift the container three meters and dividing by twenty seconds, then assuming a 50% efficiency. This resulted in a power requirement of about 70 kW.

In a similar manner, it was estimated that during land travel, the four Hi-Pa wheel motors would require 400 kW continuous power, with spikes in power requirements being handled by capacitors.

The power required for the autonomous system is the most complicated to calculated because it is composed of many different components. Five LIDAR modules use 2100 W in total. The navigation system uses 200 W and the computer uses 151 W on average. GPS components use 37.5 W. This totals to about 2.5 kW. Although the autonomous system estimate is calculated for current equipment, it shows that the autonomous system should draw relatively little power.

Because these systems are not used simultaneously, the total power required at each stage of the mission is less than 900 kW. These requirements are summarized in the table above.

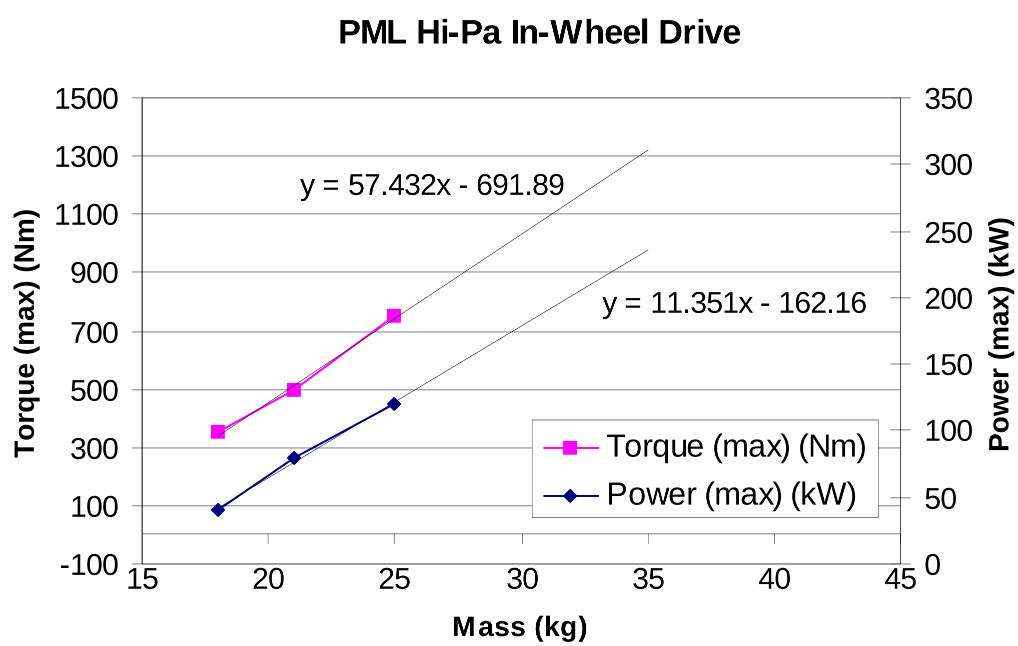


Figure 17: Hi-Pa Wheel Motor Extrapolation Curves

A straight line was fitted through the three data points given by PML. This curve was used to determine an approximate weight required for a given maximum torque. The maximum torque required for the DUKW 21 was assumed to be the torque required to move the DUKW up a 3 degree slope.

Item	Estimated Weight (kg)	Margin (%)	Adjusted Weight (kg)	Weight (lbs)	Percent of Total
Hull and Frame					
Skin Plating and stiffening	3,500	10%	3,850	8,488	6.8%
Internal Structure (bulkheads)	600	30%	780	1,720	1.4%
Arch structure	3,900	10%	4,290	9,458	7.6%
Helm structure, controls, seat and pilot	350	20%	420	926	0.7%
Turbine enclosure and air intake	350	10%	385	849	0.7%
Paint	40	10%	44	97	0.1%
Total	8,740		**9,725**	21,440	17.3%
Power Pack and Drive Train					
Turbine Generator Set	1,134	5%	1,191	2,625	2.1%
Hi-Pa wheel motor x4	200	50%	300	661	0.5%
Super-capacitors and batteries	760	20%	912	2,011	1.6%
Rim Driven Podded Propulsor x 2	910	20%	1,092	2,407	1.9%
Hydraulic Retraction and Steering System	600	30%	780	1,720	1.4%
Total	3,604		**4,275**	9,424	7.6%
Suspension, Tracks, Steering					
Suspension and Steering	6,000	15%	6,900	15,212	12.2%
Tracks - L	2,400	15%	2,760	6,085	4.9%
Track - R	2,400	15%	2,760	6,085	4.9%
Total	10,800		**12,420**	27,381	22.0%
Fire Control					
Automatic Fire Extinguishing System	90	10%	99	218	0.2%
Total	90		**99**	218	0.2%
Autonomy and Control					
Comm and Nav Equipment	136	20%	163	360	0.3%
electronics	182	10%	200	441	0.4%
Total	136		**163**	360	0.3%
Bilge System					
Bilge Pump x4	120	10%	132	291	0.2%
Total	120		**132**	291	0.2%
Container Dismount System					
spreader bar, cables, pulleys	1500	20%	**1,800**	3,968	3.2%
winches (x4)	1180	5%	**1,239**	2,732	2.2%
Total	2680		**3,039**	6,700	5.4%
Total Unloaded Weight	**26,170**	14.1%	**29,853**	65,814	**53%**
Payload					
20 Foot ISO	24,000	0%	**24,000**	52,911	42.6%
Fuel (10 Trips)	2382	5%	2,501	5,514	4.4%
Total	26,382		**26,501**	58,425	47.0%
Total Vehicle Weight	**52,552**	7.2%	**56,354**	124,239	**100%**

Table 14: Detailed Weight Breakdown

Item	Adjusted Weight (kg)	location X	Y	Z
Hull and Frame				
Skin Plating and stiffening	3,850	7.5		1
Internal Structure (bulkheads)	780	7.5		1
Arch structure	4,290	7.2		4.5
Helm structure, controls, seat and pilot	420	12.5	2.7	3
Turbine enclosure and air intake	385	5.5		3
Paint	44	7.5		4
Total	**9,725**			
Power Pack and Drive Train				
Turbine Generator Set	1,191	5.5	-2.8	2.5
Hi-Pa wheel motor x4	300	13.2		0.6
Super-capacitors and batteries	912	11	1	2
Rim Driven Podded Propulsor x 2	1,092	-0.5		0.7
Hydrolic Retraction and Steering System	780	-0.5		1.5
Total	**4,275**			
Suspension, Tracks, Steering				
Suspension and Steering	6,900	7.8		0
Tracks - L	2,760	7.8		0
Track - R	2,760	7.8		0
Total	**12,420**			
Fire Control				
Automatic Fire Extinguishing System	99	7.5		2
Total	**99**			
Autonomy and Control				
Comm and Nav Equipment	163	9	2.6	1.6
electronics	200	9	1	1.6
Total	**163**			
Bilge System				
Bilge Pump x4	132	7.5		0.1
Total	**132**			
Container Dismount System				
spreader bar, cables, pulleys	**1,800**	7.2	0	5.5
winches (x4)	**1,239**	7.2		6.7
Total	**3,039**			
Total Unloaded Weight	**29,853**	**7.258**	**-0.022**	**1.756**
Payload				
20 Foot ISO	**24,000**	7.2	0	4.1
Fuel (10 Trips)	2,501	4		1.5
Total	**26,501**			
Total Vehicle Weight	**56,354**	**7.089**	**-0.012**	**2.743**

Table 15: CG Calculation